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SCHOOL OF APPLIED SCIENCE

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Critical evaluation of Compost Erosion Control Blankets (CECBs) against conventional Best Management Practices (BMPs) for the prevention and control of soil erosion, nutrient loss and storm water runoff from engineered slopes under simulated UK conditions

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Abstract

In recent decades increasing attention has been dedicated to issues of sustainable land management. Soil is essential for a number of functions and services which are central to the sustainability of agro-ecosystems and the global economy. Consequently soil management and specifically soil erosion including, erosion from construction activities, is moving up the political and legislative agenda. This thesis investigated the suitability of Compost Erosion Control Blankets (CECBs) for runoff and erosion control, on construction sites under two simulated rainfall events (5 and 75 year return period storm events (PRSE)) as compared with currently adopted Best Management Practices (BMPs). Two grades of BSI BSI PAS 100:2005 compost, namely $CECB_{0\text{-}20mm}$ and $CECB_{0\text{-}40mm}$, were tested against two Erosion Control Blankets (ECBs), namely ECB_{straw} and ECB_{coir}, and control bare soil plots. Treatment performance was evaluated in terms of a range of attributes including runoff rate, volume and time to runoff initiation and total suspended solid TSS and nitrogen and phosphorous levels in runoff. In addition, nitrogen and phosphorous levels in leachate were also investigated.

The potential of CECBs as an adoptable erosion control technique was relevant only for the 5yr PRSE, due to their greater water storage capacity (WSC). However, once the CECBs became saturated, at different time in relation to the soil type, the runoff rate was greater than all other treatments including the control. As a consequence the performance of the CECBs in terms of storm water management is highly variable and dependent on the storm duration. Another source of uncertainty with regards to the use of CECBs for runoff and erosion control is that their physical behaviour changed in relation to the soil type used.

With the exception of nitrate-N, the CECBs did not demonstrate an offsite risk of water contamination. The concentration of potential contaminants, namely ammonium-N and orthophosphate-P, released via runoff and leachate were comparable to the levels released from the other treatments.

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List of abbreviation

AASHTO	American Association of State Highway Transportation Officials
Ammonium-N	Ammonium
BD	Bulk Density
BMPs	Best Management Practices
BSI	British Standards Institution
$CECB_{0\text{-}20mm}$	Compost Erosion Control Blankets PSD 0-20mm (AASHTO not compliant)
$CECB_{0\text{-}40mm}$	Compost Erosion Control Blankets PSD 0-40 mm AASHTO compliant)
CECBs	Compost Erosion Control Blankets
DEFRA	Department for Environment Food and Rural Affairs
ECB_{coir}	Coir Erosion Control Blankets
ECBs	Erosion Control Blankets
ECB_{straw}	Straw Erosion Control Blankets
ECTs	Erosion Control Treatments
ETCs	Erosion Control Techniques
Exp_{WB}	Experimental Water Balance
N	Nitrogen
NPDES	National Pollutant Discharge Elimination System
Orthophosphate-P	Orthophosphate
P	Phosphorous
PAS	Publicly Available Specification
PRSE	Period Return Storm Event
RCBD	Randomize Complete Blok Design
SBP	Sediment Bound Phosphorous
TON	Total Oxides of Nitrogen
TSS	Total Suspended Solids

USEPA	United States Environmental Protection Agency
WRAP	Waste and Recycling Action Programme
WS	Water Storage
WSC	Water Storage Capacity

1 Introduction

1.1 Background

In recent decades increasing attention has been dedicated to issues of sustainable land management. This is mainly due to the rapid increase in human population that has resulted in increasing demands placed on agricultural and urban lands (Hudson, 1995). One of the most important processes leading to soil and water degradation is soil erosion by water (Zheng et al., 2005). Soil is essential for a number of functions and services (Table 1.1) which are central to the sustainability of agro-ecosystems and the global economy (DEFRAa, 2009).

Table 1.1 Soil functions and services (DEFRAa, 2009)

Services	Function
Provisioning	Livelihoods and food security
Supporting	Soil formation, primary production, water and nutrient turnover
Regulatory	Soil moisture storage, ground water re-charge, flood mitigation and water regulation
Erosion Regulation	Vegetative cover, root stabilization , aggregate stability
Water Purification/Waste Treatment	Domestic and industrial water supply, aquatic ecosystems
Climate Regulation	Global carbon sequestration, regional changes in rainfall patterns, local micro-climates
Cultural	Cultural heritage values

Considering the long time frame for pedogenesis, soil can be thought of as a non-renewable resource (DEFRAa 2009), consequently soil management and specifically soil erosion is moving up the political and legislative agenda. The rates of soil formation vary according to the influences of several factors such

as climate, substrate and land use. For un-disturbed conditions soil formation rates range from 0.025 to 0.083 mm yr-1 (Troeh and Thompson, 1993; Lal and Stewart 1990).
As a consequence the EU Thematic Strategy for Soil Protection (Van-Camp et al., 2004) lists soil erosion as a major threat to soil resources and one of the three priority areas for policy recommendations. This is reflected in the emphasis placed on soil erosion in the draft Soil Strategy for England (DEFRAa, 2008) and the concern over Total Suspended Solids (TSS) and sediment bound pollutants (primarily Phosphorous (P) and Nitrogen (N) within the EU Water Framework Directive (European Commission, 2000). In addition, DEFRA has recently released a consultation document entitled "Code of Practice for the Sustainable Use of Soils on Construction Sites" (DEFRAb, 2009).

Soil erosion is a three-phase process involving soil particle detachment, transport and deposition. The first phase is soil particle disaggregation and detachment, caused directly by rain splash, running water and/or wind. Weathering processes, like freezing and thawing, alternate wetting and drying, thermal excursion and tillage operations can also weaken the soil structure and promote disaggregation (Morgan, 2005). Under the mid-latitude oceanic climate conditions, occurring in the UK (Pidwirny, 2006), rainfall is the most relevant detaching agent. Soil particle disaggregation hazards are usually more pronounced on bare soil, as vegetation has a positive effect on reducing erosion by intercepting rainfall and reducing its energy and therefore aggregate breakdown (Morgan and Rickson, 1995). At this stage, soil detachment and thus erosion control can be achieved by protecting the soil surface from the erosive energy of raindrop impact. This can be achieved by promoting re-vegetation, a long term process, or by covering the soil with products that provide immediate surface protection such as Erosion Control Blankets (ECBs).

Following aggregate breakdown and the supply of disaggregated material, the second phase of the erosion process consists of the transportation of detached soil particles by water or wind. The final phase, deposition occurs when the energy of the transporting agent is insufficient for particle transportation.

Several direct and indirect environmental consequences are related to soil erosion. On-site effects include the loss of soil structure, impoverishment of organic matter and nutrients through loss of top soil. Crust formation or reduced infiltration capacity can reduce soil productivity, plant water availability and also ground water recharge (Fetter, 1988). Furthermore runoff shortens the time to peak discharge, changes the flood hydrograph and can initiate gully formation.

Numerous off-site consequences are associated with sediment transported by runoff (Grismer and Hogan, 2005; Chatterjega, 2009). Sediment can obstruct drainage channels, thus increasing flooding risk, increase the maintenance costs associated with harbours and dams, and can cause drastic changes in coastal ecosystems. In addition, sediment bound and water soluble contaminants can pollute water courses (Novotny and Olem, 1994), increasing the cost of water treatment. Nutrients such as N and P can also be washed into water bodies causing eutrophication, thus promoting aquatic plant and algal growth (DEFRA, 2010).

In terms of soil erosion and its control, in the UK, USA as well as Europe, increasing attention is being focused on construction sites. Due to their physical characteristics engineered slopes are areas particularly vulnerable to runoff and erosion (Environment Agency, 2007).

A wide range of erosion control techniques has been applied on engineered slopes and over the last 10 years research undertaken in the USA has demonstrated the effectiveness of Compost Erosion Control Blankets (CECBs) at reducing soil and nutrient losses, as well as controlling storm water flows from construction sites both during and after the construction phase (Faucette et al., 2004; 2005; 2006; 2008; Keener et al., 2007).

As a result, CECBs are accepted as Best Management Practices (BMPs) by the United States Environmental Protection Agency (USEPA, 2006a; 2006b) as well as the National Pollutant Discharge Elimination System (NPDES), and are adopted as a BMPs by the American Association of State Highway Transportation Officials (AASHTO) and several state-level Departments of Transport.

1.2 Aim

The aim of this research is to critically evaluate the performance of CECBs as compared with conventional ECBs, for the prevention and control of soil erosion, nutrient loss and storm water runoff from engineered slopes under simulated UK conditions.

1.3 Objectives

1. To critically evaluate the impact of rainfall event on runoff and erosion control performance of CECBs compared with conventional ECBs.

2. To evaluate the influence of slope gradient on efficacy of CECBs, to reduce runoff and erosion.

3. To assess influence of compost particle size on CECBs runoff and erosion control performance.

4. To assess water contamination (P and N) hazard derived from CECBs application.

1.4 Hypotheses

Based on the literature review and an evaluation of the gaps in knowledge, the hypotheses tested in this thesis are as follows:

1. Slope gradients influence the performance of CECBs.
2. CECBs are significantly better than current BMP in the prevention and control of soil erosion, nutrient loss and storm water runoff from engineered slopes under simulated UK conditions.
3. The PSD of BSI PAS100:2005 compost has a significant effect on performance of the CECBs.
4. CECBs are associated with higher levels of N and P in both runoff and leachate as compared with the current BMPs tested and the untreated controls.
5. The performance of CECBs is consistent across soil types.

2 Literature review

2.1 Soil erosion and runoff from engineered slopes

It is well recognized that anthropogenic activities, including deforestation (Sahin and Hall, 1996, Zheng et al., 2005; Chaves et al., 2008), farming (Graef and Stahr, 2000, Boardman et al., 2009), grazing (Pietola et al., 2005), and infrastructure construction, can influence small and large scale hydrological systems (Harden, 2006; Chatterjea, 2009). Engineered slopes associated with roads, railways and other constructions, can generate high rates of soil erosion (Chatterjea, 2009; Grismer and Hogan 2005). In a study carried out by the Georgia Soil and Water Conservation Commission (2002), it was found that the rate of soil loss from construction sites can be 200 times the soil loss of forest lands, and 10 to 20 times that of agricultural areas.

The susceptibility of engineered slopes to soil erosion is due to the interaction of several different factors. These include:

- Heavy machinery compacting the soil, thus reducing its saturated hydraulic conductivity.
- Soil depletion exposes bare mineral soil to the rain drop energy.
- The lack of organic matter and soil coverage promotes structural sealing and crusting, reducing the infiltration rate (Jury and Horton, 2004; Graef and Stahr, 2000).
- The lack of nutrients and water in bare soil challenges the development of ecological successions, retarding revegetation.
- Smooth, regular and compact surfaces associated with engineered slopes promote sheet overland flow.
- Slope angles associated with engineered slopes tend to be of the length elevation rate 2:1 and 3:1 depending on the material used during the construction activity and the land available. If land is limited steep slopes will be dominant. Volume and velocity of the runoff is raised with the

increasing steepness and length of the slope. Furthermore, on sloping surfaces, depending on the angle of the raindrop when striking the ground, the particles are splashed predominantly downslope and the effect is proportional to the slope angle (Morgan, 2005).

2.2 Soil erosion and runoff control techniques

In the last decade, globally, increasing attention has been focused on controlling soil erosion and runoff from engineered slopes and numerous solutions have been proposed (Morgan and Rickson, 1995; Brofas and Varelides, 2000; Montoro et al., 2000; Zhou, 2000; Keating, 2005; Foltz and Dooley, 2004; Peterson et al., 2007; Baxter, 2008; Goldberg, 2008; Faucette et al., 2009). These include two and three-dimensional structures that mitigate erosion by reducing the runoff velocity and promoting ponding, like silt fences, geotextile berms, erosion control barriers, live barriers, and compost filter socks. Other treatments, like two- and three-dimensional ECBs, agricultural straw, wood stands, and pine needle blankets are designed to protect the soil from the effect of raindrops and to reduce the runoff speed, thus targeting the first phase of the erosion process and limiting erosion.

As environmental and structural conditions vary from site to site, it is difficult for a standardized technique to be applied. Variables such as climate, physical and chemical properties of the soil, slope steepness and aesthetic aspects are taken into account before adopting particular Erosion Control Techniques (ETCs). A summary of the currently adopted Best Management Practices (BMPs) are discussed below.

Erosion control blankets (ECBs) have been used in direct contact with or incorporated into the soil surface (Figure 2.1). They can be permanent or degradable, embrace different manufactured typologies, and be two- or three-dimensional. They include meshes, geo-textiles, natural fibre mats and honey comb shaped webs. Erosion Control Blankets can be composed of natural fibres, synthetic polymers or a combination of both (Figure 2.1).

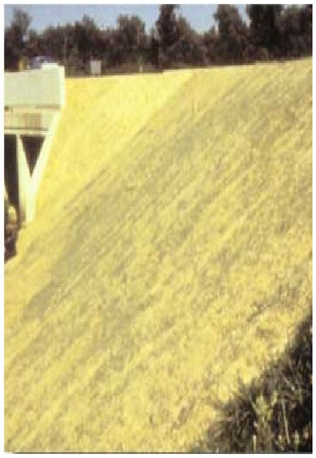
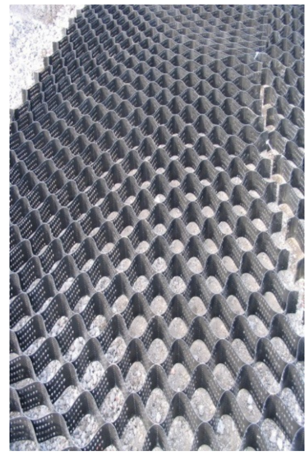
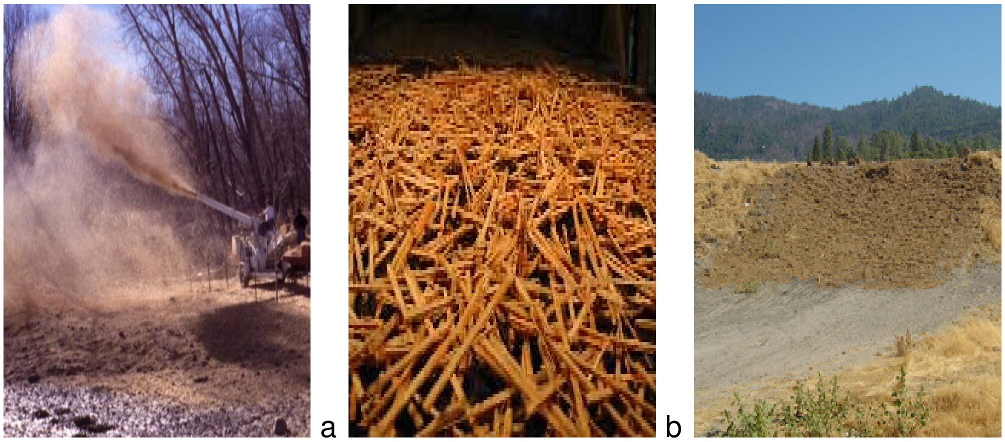
 a  b  c

Figure 2.1 a) straw fibre mat on site; b) fabric (TMP, 2009); c) honey comb cellular confinement (NILEX 2008)

ECBs are used as turf re-enforcement mats, as soil protection blankets and/or invasive plant suppressors during the process of slope re-vegetation (Tice, 2006). Erosion control blankets offer good coverage and protect the soil surface from raindrop impacts, thus preventing disaggregation, structural sealing and soil detachment (Demars and Long, 1998; ECTC, 2004; Reinsch et al., 2007; Faucette et al., 2009).

Wood stands (wood straw), made by using small diameter poles (unsuitable for other uses) can also be blown onto engineered slopes (Figure 2.2). This treatment performs as well or even better than straw mulch and seems to be a suitable replacement where the cost of using agricultural straw is too high (Foltz and Dooley, 2004). The benefits of using wood based products are that they are inherently free of noxious weed seeds and tend to be free of pesticide residues. They have a high structural integrity and a zero to low probability of producing dust or allergens during application.



a b c

Figure 2.2 a) agricultural straw application (Aquatic and Wetland Company, 2009); b) wood straw (Innovative, 2009); c) pine needles (Fire Safe, 2002)

Hydromulch and hydroseeding, a mix of fertilizers, soil stabilizers, seeds, and fibres of various genera (Montoro et al., 2000; Brofas and Varelides, 2000) have been used to protect the soil from disaggregation. They improve detachment mitigation and the saturated hydraulic conductivity of the soil. One of the greatest concerns associated with this technique is the risk of off-site contamination, due to the high fertilizer loads employed. Further, Hydromulch and hydroseeding may not provide full coverage of the soil surface as compared with ECBs and CECBs. However, they have been shown to stabilize soil aggregates, improve soil structure and infiltration rate (Peterson et al. 2007). Erosion is therefore detachment as well as transport limited.

In the UK, conventional soil erosion control measures for engineered soil slopes such as highway batters, landfills and railway cuttings/embankments are mentioned within the Highways Agency Manual of Contract Documents for Highway Works: Volume 1 Specification for Highway Works (Highways Agency 1998 plus amendments 1998-2007), Series 600 Earthworks. The Environment Agency Pollution Prevention Guidelines PPG 5 and PPG6 also mention ECBs (with or without incorporation of seeds), silt fences, hydroseeding and conventional seeding for the control of sediment on construction sites.

2.3 Compost: An alternative Best Management Practice (BMP) for erosion control

2.3.1 Compost Erosion Control Blankets (CECBs)

Compost Erosion Control Blankets (CECBs) are a soil erosion and runoff control technique adopted as BMPs by the American Association of State Highway and Transport Officials (AASHTO, 2006). They are particularly suitable for engineered slopes because these slopes tend to be uniform and well graded to avoid the occurrence of preferential flow paths.

CECBs comprise a layer of compost that is spread manually or by blower onto the soil surface. Even though the depth of the layer spread generally is 5 cm, it can vary between 3.5 and 10 cm, as determined by the location and the rainfall characteristics. The compost can contain seeds or can be seeded post-application. They are detachment and transport limiting, by offering full soil coverage. CECBs have also been shown to reduce runoff by retaining water due to their high Water Storage Capacity (WSC) (Singer et al., 2006).

In the USA, the physical characteristics of compost used for CECBs should be compliant with the AASHTO specifications listed in Table 2.1 (Alexander, 2003). Particular attention should be given to the particle size distribution of the compost to be applied. Soil loss and suspended solids can be four and five times higher when using CECBs that do not meet AASHTO and USEPA particle size distribution specifications (Faucette et al., 2007). The larger compost fraction (> 20 mm) absorbs the rainfall's kinetic energy, thus preventing splash detachment and soil dislodgement. In addition, the larger compost fraction reduces sediment transport in overland runoff by reducing runoff rates due to their size and weight.

In contrast, the smaller compost fraction (< 20 mm) improves the compost's Water Storage Capacity (WSC). Additionally, CECBs provide nutrients and a substrate for the re-vegetation process (Faucette, 2007).

CECBs are particularly suitable for the prevention of sheet runoff. They protect the soil surface, thus preventing or minimising raindrop impact. They further retain the rainfall (volume) by acting as a reservoir. CECBs can be used in association with other runoff and erosion control techniques, including geotextile berms, erosion control barriers, live barriers, or filter socks (Faucette et al., 2005).

Documented advantages of CECBs over conventional (non-seeded) ECBs (Faucette et al., 2005, 2006, 2007, 2009; Glanville et al., 2004; Reinsch et al., 2007) include:

- Retention of a larger volume of water, thus delaying the onset of overland flow, reducing runoff volume and preventing/reducing sheet and rill erosion.
- Increased protection of the soil surface from rainfall energy (provides 100% cover as compared to 75-80% cover provided by conventional ECBs), thus preventing splash detachment, structural sealing and crusting, thus facilitating infiltration.
- Better germination and vegetation establishment, reducing fertilizer use.
- Weed suppression, reducing the use of herbicides.

Table 2.1. AASHTO physical specifications for compost used for CECBs (Alexander, 2003).

Parameters	Units	Value
Moisture content	wet weight basis	30-60%
Organic matter	dry weight basis	25-100%
Particle size	passing a selected mesh size, dry weight basis	75 mm, 100%
		22 mm, 90% to 100%
		19 mm, 65% to 100%
		6.4 mm, 0% to 75%
		Maximum particle length of 152 mm
Physical Contaminants (man-made inerts)	dry weight basis	< 1%

2.3.2 Composting in the UK

Large scale composting in the UK is regulated by a series of acts and regulations, partly derived from EU directives and national laws. EU regulations for waste management are encompassed within the Framework Directive on Waste, 75/442/EEC, as amended by 91/156/ECC.

In the UK, the WRAP (Waste and Resources Action Programme) is an organization that helps businesses and individuals reap the benefit of reducing waste, developing sustainable products and using resources in an efficient way. Together with the Association for Organics Recycling, they are the foremost organizations for the biodegradable waste management industry.
The aim of these organizations is to raise awareness of the benefits of the recycling of biodegradable resources. They envisage an industry in which best practice is shared, standards are maintained and surpassed and which makes a positive contribution to safeguarding the environment.

A brief explanation of acceptable compost manufacturing methodologies for large scale composting in the UK is given by Gilbert et al. (2001).

For yard waste compost manufacturing, the feedstock should be collected separately to avoid contamination with non-compostable man-made inerts such as glass, plastic, metal objects etc. After evaluating the suitability of the feedstock by visual inspection, the material to be composted is shredded, ground and then stacked in windrows (Figure 2.3). The simplest way to promote aeration is by convection, driven by the stale air and hot water vapour. Periodically the material should be mixed mechanically. Moisture and temperature are inspected regularly to control microbial activity. When the temperature decreases to ambient temperature, the compost reaches stability, though some microbial activity can still take place. After stabilization, maturation will take place, to terminate the residual microbe activity. Maturation requires between one to six months, during which time the compost will ideally be covered to prevent potential contamination (Gilbert et al., 2001).

Figure 2.3 Compost windrow at MEC, a Lincoln-based recycling facility

2.3.3 BSI PAS (Publicly Available Specification) 100:2005 certification

BSI PAS 100:2005 entails a series of specific requirements for biodegradable materials that have been separately collected from non-biodegradable, and that have not been mixed, combined or contained within other potentially polluting wastes. The requirements specify the upper limits for potentially toxic elements, physical contaminants, and indicators of human and animal pathogens.

Compost can contain contaminants and pathogens which can be hazardous for plant, animal and human health. Trace elements include cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni) and zinc (Zn) which, if contained in the compost can affect CECBs suitability for runoff and erosion control, since these elements can directly affect soil and water quality. In England compost should be produced according to the British Standards Institution Publicly Available Specifications (BSI PAS) 100:2005. The specifications regard the quality of the product and the minimum requirements of compost manufacturing. The composted products shall not contain toxic substances and not cause noxious odours. The feedstock used to make it, and its traceability, should be specified. Furthermore particle size distribution, moisture, stones and weed propagules, as well as physical and chemical contaminants should be within the specifications listed in Table 2.3.

Table 2.2 BSI PAS 100:2005 Compost specifications, physical and chemical contaminant limits

Contaminants	Units of measure	Limits
Chemical		
Cadmium (Cd)	mg kg^{-1} dry matter	≤ 1.5
Copper (Cu)	mg kg^{-1} dry matter	≤ 1.6
Chromium (Cr)	mg kg^{-1} dry matter	≤ 1.7
Lead (PB)	mg kg^{-1} dry matter	≤ 1.8
Nikel (Ni)	mg kg^{-1} dry matter	≤ 1.9
Mercury (Hg)	mg kg^{-1} dry matter	≤ 1.10
Zinc (Zn)	mg kg^{-1} dry matter	≤ 1.11
Biological		
Salmonella	MPN / 25 g	Absent
Escherichia coli	CFU g^{-1}	≤ 1000 CFU g^{-1}
Weed Seeds	Viable propagules/litre	≤ 5 maximum
Phytotoxicity	Score % of control	80% minimum
Physical		
Total glass, metal and plastic	% sample>2mm	≤ 0.5
of which plastic	% sample>2mm	≤ 0.25
Stones and other consolidated	% sample>2mm	≤ 7

2.3.4 Levels of Phosphorous (P) in BSI PAS 100:2005 compost

Even though maximum permissible values for P are not included in the BSI PAS 100:2005 specifications, increasing P concentrations in rivers are known to change the biomass and composition of biological communities. This enhances plant and algal production, consequently the release of runoff with a high concentration of P should be restricted. The UK water quality standard in relation to soluble-P in rivers, is based on the annual mean, and is specified in the final report of the Water Frame Work Directive of the UK Environmental Standard and Condition, (Phase-1) (WFD UK TAG, 2008). Table 2.3 shows the four water quality categories for the UK in relation to soluble-P concentrations. As the P solubility depends on pressure and alkalinity, Table 2.4 shows the four categories of water quality taking these two variables into account.

Table 2.3 River typologies in relation to elevation (m) and alkalinity (mg l^{-1})

Altitude (m)	Annual mean alkalinity (as mg l^{-1} calcium carbonate)	
	< 50	> 50
Under 80 m	Type 1	Type 3
Over 80 m	Type 2	Type 4

Table 2.4 River water quality, relative to soluble reactive phosphorus concentrations (mg l^{-1})

Type	High (mg l^{-1})	Good (mg l^{-1})	Moderate (mg l^{-1})	Poor (mg l^{-1})
1	30	50	150	500
2	20	40	150	500
3 and 4	50	120	250	1000

If CECBs generate levels of P in runoff that exceed EU max permissible levels, although they may be effective for erosion control, they cannot be adopted as they will impact on the water quality. Consequently, levels of P in runoff will be evaluated in this thesis.

In compost the total P is classified in relation to its form, namely bioavailable inorganic, potentially bioavailable inorganic, readily mineralizable organic or potentially bioavailable organic P (Zhang et al., 2004). Bioavailable inorganic P is an anionic form that occurs primarily as hydrogen phosphate ($H_2PO_4^{2-}$) and di-hydrogen phosphate ($H_2PO_4^{-}$) and is the form of P most commonly found in leachate and runoff generated from yard waste compost (Confesor, 2009). Readily mineralizable organic and potentially bioavailable organic P are to be found in the form of fulvic acid, humic acid, phospholipids, and nucleic acid. These are present as compounds in dynamic transformation with the compost' s organic matter (Sharpley, 2000). Potentially bioavailable inorganic P exists in the form of amorphous and crystalline sesquioxides, calcareous compounds or bound to the mineral fraction, and cannot be leached (Rowell, 1994). Potentially bioavailable inorganic P becomes available for the plant whenever the concentration of its dissociated form becomes low, due to the plant uptaking hydrolysed P from the soil water. Furthermore, it has been demonstrated (Zhang et al., 2004) that compost rich in iron (Fe), aluminium (Al) and calcium (Ca) effectively immobilizes P.

2.3.5 Levels of Nitrogen (N) in BSI PAS 100:2005 compost

As with BSI PAS 100:2005 does not specify limits for N even though compost is particularly N-rich (Haug 1993), and high concentrations of inorganic N in a water body can produce eutrophication (Novotny and Olem, 1994). Furthermore, high concentrations of soluble-N are hazardous for animal and human health whenever they reach a ground water reservoir or water body designated to provide drinking water. Therefore, according to the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government, 2008) to consider fresh water unpolluted, the concentration of nitrate-N has to be less than 50 mg l^{-1}. Even though BSI PAS 100:2005 does not specify limits for compost, if CECBs will generate levels of N in runoff and/or leachate that exceed the limits for unpolluted water, their use could be restricted.

In general, N in compost is present in its organic form, as insoluble acids, amino acids, and amino sugars. It is not soluble in water but can be carried by the water, bound to transported particles. The only N that may leach from

CECBs is inorganic nitrite (NO_2^-) and nitrate (NO_3^-). Ammonium-N (NH_4^+) is mostly present as an exchangeable cation, thus its presence in water is limited (Black, 1968). Confesor et al., (2009) evaluated the N contamination risk, using soil columns and tested three compost typologies derived from different waste streams (farm, food and yard waste) and stages of maturation (3, 6, 9, 12 and 15 weeks). The results indicate that yard waste compost contains total N concentrations (1000 mg^{-l}) lower than the other products, and that this value decreases over time.

2. 4 Performance of CEBCs at mitigating soil erosion and controlling runoff

2. 4. 1 Current understanding of CECBs performance

The current understanding of the performance of CECBs is primarily associated with research undertaken in the USA, since CECBs have been used there as BMPs for more than 10 years. For the UK and Europe in general it is a novel field of research and as a result there is no literature available.

The existent literature (Faucette et al., 2005, 2006, 2007, 2009; Glanville et al., 2004; Reinsch et al., 2007; Singer et al., 2006) evaluates the performance of CECBs for erosion control without taking into account the possible variations in performance resulting from testing the same treatment on different soil types. Because of the complexity of the soil system, and the extreme diversity of chemical and physical soil characteristics, it is intuitive that a given CECB specification will perform differently in relation to the soil type used.

This has to be a relevant factor to be considered, and more research needs to be done in order to define the relationship between soil type and CECBs performance. This thesis seeks to address this gap in knowledge.
Again, as most of the research related to CECBs has been undertaken in the USA, there is a lack of literature in relation to the CECBs performance under UK climate conditions (Pidwirny, 2006). Rain intensity and duration is crucial in order to understand the efficiency threshold of CECBs in relation to different precipitation regimes.

All previous research undertaken to assess the contamination hazard associated with the use of CECBs has focused on potential off site impacts associated with runoff. No studies have evaluated the potential contamination hazard associated with the vertical movement of rainfall through the CECB and into the underlying soil. This is a critical oversight as the compost leachate could contaminate the underlying aquifer. This gap of knowledge is in part addressed by this thesis.

2.4.2 Previous research

The effectiveness of CECBs as runoff and soil erosion control, by reducing raindrop energy, particle detachment, and retaining water is well documented (Faucette et al., 2005, 2006, 2007, 2009; Glanville et al., 2004; Reinsch et al., 2007; Singer et al., 2006). A short description of the testing conditions, are given in Table 2.5.

Table 2.5 Previous researches on CECBs regarding runoff and erosion control

Treatment	Slope	Soil Type	Reference	Country
CECBs	10:1	Pacolet Sandy Clay Loam	Faucette et al., 2006	USA
	10:1	Pacolet Sandy Clay Loam	Faucette et al., 2007	USA
	2:1;3:1; 4:1	Loamy Sand	Faucette et al., 2009	USA
	3:1	no information	Glanville, 2004	USA
	3:1	Clay	Reinsch et al., 2007	USA
	18:1 to 10:1	Coarse glacial till	Singer et al., 2006	USA

Glanville et al., (2004) demonstrate how CECBs made of yard waste compost are efficient in reducing runoff and soil erosion without contamination risk as compared to other compost typologies. Glanville et al., (2004) evaluated the performance of 5.0 cm CECBs derived from four different waste streams as compared with a 15 cm topsoil application and untreated control. Runoff initiation, total runoff volume, TSS, total-N, ammonium-N, and total-P were evaluated from roadway embankment plots of 3:1 slope, in 50 × 75 cm test areas, under high rainfall intensity (100 mm h-1 for 30 min). Table 2.6 shows how CECBs derived from yard trimmings reduced runoff and TSS loss and delayed runoff initiation more effectively as compared with the untreated control.

Table 2.6 Total runoff, TSS and nutrient loss from CECBs as compared with an untreated control (Glanville et al., 2004)

Variable	CECB biosolid	CECB yard trimming	CECB bio-industrial	Control	Top soil
Runoff (mm)	0.13	<0.01	0.08	26.2	15.5
Time to runoff initiation(min)	31.1	56.9	32.2	4.67	7.83
TSS (mg)	7.84	0.02	2.52	43000	40000
NO_3^- (mg l^{-1})	1.08	30.4	8.57	1.71	2.07
NH_4^+ (mg l^{-1})	5.91	2.07	90.01	0.72	1.74
Orthophosphate-P (mg l^{-1})	3.10	1.26	0.36	0.14	0.13
Sediment bound P (mg kg^{-1})	4300	6400	2350	2430	2430

Runoff volume, TSS and nutrients loads from experimental plots were also measured by Reinsch et al., (2007). CECBs (waste yard compost) were compared to a BMP treatment (straw mat) and control (bare soil), on 3.0 m x 12.0 m plots on a 3:1 slope over two seasons (April-November, May-August) under natural rainfall plus three identical simulated events of 50 minutes duration, 64 mm hr^{-1}). The subsoil was predominantly clay and the top soil was removed from every plot to simulate an engineered slope. Table 2.7 illustrates the effectiveness of CECBs at reducing runoff and TSS.

Table 2.7 Effect of CECB and BMP treatments on total runoff and percentage of runoff reduction and TSS load (adapted from Reinsch et al., 2007)

Treatment	Total runoff (mm)	Runoff reduction (%)	TSS load (kg)
Control	190	-	180
Straw mat	135	29%	12
CECB	8.2	96%	0.56

The performance of CECBs with different PSD was tested in comparison with a straw blanket + polyacrylamide and control on 1.0 x 4.8 m plots by Faucette et al., (2007). All the treatments were tested on Pacolet Sandy Clay Loam, 10:1 slope, with an extreme simulated storm event (intensity of 100 mm h-1 and duration of 1 hr). To determine the effectiveness of the CECBs, analysis of storm water quantity and quality included total runoff volume, and percent of runoff from rainfall, elapsed time until runoff commencement, total sediment load, N-load, and P-load were evaluated.

Faucette et al., (2007) suggest that the CECBs, as compared to the control, reduced storm water runoff volume by 52%, total sediment load by 93%, and increased the time to runoff commencement six fold. CECBs did not contribute any soluble P to runoff, but increased of 340% the total Kjeldahl-N, compared to the control plot.

Faucette et al., (2009) again tested the performance of green waste compost blankets with 3 different thickness, (1.25, 2.5 and 5.0 cm), as compared with 4 different ECBs (single- and double-net straw blankets; double-net coconut fibre blanket; and a single-net excelsior wood-fibre blanket). The treatments were tested on 3 different slope gradients (2:1; 3:1; 4:1) under simulated rainfall. The initial intensity was 50 mm h^{-1} for 20 min, followed by 100 mm h^{-1} for 20 min, followed by a peak intensity of 150 mm h^{-1} for 20 minutes. Taking into account only the 50 mm h^{-1} storm, a comparison on runoff and erosion control of the 5.0cm CECB versus control and ECBstraw is shown in Table 2.8.

Table 2.8 Effect of CECB and BMP treatments on total runoff and percentage of runoff reduction and TSS load (adapted from Faucette et al., 2009)

Treatment	Runoff (l)	TSS (kg)	TSS reduction (%)
Control	133	38	--
CECBs	77	0.08	99.8%
ECBstraw	83.2	14	7.7%

2.5 Chapter summary

CECBs are detachment limiting soil erosion and runoff control techniques. They provide full coverage for the soil, prevent slaking, disaggregation, structural sealing and crust formation. Furthermore, the WSC of CECBs delays runoff initiation and reduces runoff volume (Faucette et al., 2005, 2006, 2007, 2009; Glanville, 2004; Reinsch et al., 2007; Singer et al., 2006). However, nutrients integrated in the compost can be hazardous if released into the environment at concentrations exceeding national guidelines.

Using compost is an excellent means of recycling; one of the most efficient ways of using tons of organic waste produced every day. If not directed to the composting facility, this material would be piled in landfill sites. Valuable space would be occupied and hazardous pollutants would be produced, when anoxic decomposition conditions predominate. In terms of market potential, the demand for compost still remains low as compared to the quantities being produced. Erosion control practices for engineered slopes could be a viable way of utilizing surplus production. Furthermore, soil plays a fundamental role in the global carbon cycle. At a global scale, using compost for erosion control has the double benefit of C sequestration, in accordance with the carbon sequestration management policy, and increasing nutrient re-cycling efficiency (Delgado and Follet, 2002).

3 Materials and methods

3.1 Experimental design

3.1.1 Treatments

The experimental treatments are listed in Table 3.1. The experimental programme followed a randomized complete block design (RCBD).

Table 3.1 Experimental design

Soil Type	Slope	Treatment	Number of Replicates
Sandy Loam	2:1	CECB0-20mm	3
		CECB0-40mm	3
		ECB_{straw} (ECSC-2) was provided by East Coast	3
		ECB_{coir} (Type 4K)	3
		Control (Bare Soil)	3
	3:1	CECB0-20mm	3
		CECB0-40mm	3
		ECB_{straw} (ECSC-2) was provided by East Coast	3
		ECB_{coir} (Type 4K)	3
		Control (Bare Soil)	3
Clay Loam	2:1	CECB0-20mm	3
		CECB0-40mm	3
		ECB_{straw} (ECSC-2) was provided by East Coast	3
		ECB_{coir} (Type 4K)	3
		Control (Bare Soil)	3
	3:1	CECB0-20mm	3
		CECB0-40mm	3
		ECB_{straw} (ECSC-2) was provided by East Coast	3
		ECB_{coir} (Type 4K)	3
		Control (Bare Soil)	3
Silty Loam	2:1	CECB0-20mm	3
		CECB0-40mm	3
		ECB_{straw} (ECSC-2) was provided by East Coast	3
		ECB_{coir} (Type 4K)	3
		Control (Bare Soil)	3
	3:1	CECB0-20mm	3
		CECB0-40mm	3
		ECB_{straw} (ECSC-2) was provided by East Coast	3
		ECB_{coir} (Type 4K)	3
		Control (Bare Soil)	3
Total			90

3.1.2 Experimental condition and variables

Slope gradients evaluated in this study, namely 2:1 and 3:1 (horizontal:vertical), are in compliance with the Highways Agency Manual of Contract Documents for Highway Works: Volume 1, Specification for Highway Works (Highways Agency 1998 plus amendments 1998-2007), Series 600 Earthworks.
Particle size distribution is critical to both CECBs performance (Faucette et al., 2007; Keener at al., 2006). The performance of all treatments evaluated in this thesis will be assessed against both 2:1 and 3:1 slopes. In the US, the USEPA/AASHTO particle size specifications are accepted and promoted as the industry standard. Further, soil loss and suspended solids can be four and five times higher from CECBs that do not meet AASHTO and USEPA particle size distribution specifications (Faucette et al., 2007). Consequently, the proposed research will evaluate both BSI PAS 100:2005, 0-20 mm grade compost without modification of particle size distribution ($CECB_{0\text{-}20mm}$) and BSI PAS 100:2005, 0-40 mm grade compost which is compliant with AASHTO particle size distribution specifications ($CECB_{0\text{-}40mm}$).

In addition, it is generally accepted that climate change will result in significant changes in the amount, frequency, type, intensity and kinetic energy of rainfall experienced in the UK, with an increasing propensity for 'heavy' and 'extreme' rainfall events. To ensure that such changes in 'rainfall extremes' are taken into account within the experimental design performance will be evaluated for two rainfall events, namely 68mm hr^{-1} 15 minute duration which represents a 5 year return period storm event (PRSE) and 68mm hr^{-1} 30 minute duration representing a 75 year return period storm event (NERC Flood Studies Report, 1975). Rainfall will be simulated using a pre-calibrated pressurized full cone nozzle simulator. Performance will be evaluated in terms of

- Time to runoff initiation (min)
- Total runoff volume (ml)
- Mean runoff rate (ml s^{-1})

- Total leach volume (ml)
- Total suspended solids (TSS) per plot (g)
- Total suspended solids (TSS) concentration (g l^{-1})
- Runoff Total Oxides of Nitrogen (TON) concentration (mg l^{-1})
- Runoff total loss of TON per plot (mg $plot^{-1}$)
- Runoff ammonium-N (NH_4^+) concentration (mg l^{-1})
- Runoff ammonium-N (NH_4^+) per plot (mg)
- Runoff orthophosphate-P concentration (mg l^{-1})
- Runoff orthophosphate-P per plot (mg)
- Runoff Sediment Bound Phosphorous (SBP) concentration (mg kg^{-1})
- Runoff SBP per plot (mg)
- Leachate TON concentration (mg l^{-1})
- Leachate TON loss per plot (mg)
- Leachate ammonium-N (NH_4^+) concentration (mg l^{-1})
- Leachate ammonium (NH_4^+) (mg)
- Leachate orthophosphate-P concentration (mg l^{-1})
- Leachate orthophosphate-P per plot (mg)

3.2 Physical and chemical characteristics of the test soils

The physical and chemical characteristics of the three different soil types used during the experiment are given in Table 3.2 which represents the mean value of six soil sub-samples randomly selected from the bulk soil. Factorial ANOVA was applied to detect differences between the soil characteristics.
The analytical methods adopted for the soil's physical and chemical characteristics are as follows:

- NR-SAS / SOP 1 (Sample receipt, storage, preparation and disposal). The sample material was received, stored prior and during analysis in a manner that best suited the analytical requirements [BS 7755 Section

2.6 (1994) *Guidance on the collection, handling and storage of soil for the assessment of aerobic microbial processes in soil*, BS ISO 11464:2006 *Pretreatment of samples for physico-chemical studies* and Method 1 of the MAFF Reference Book RB427 (1986) *Analysis of Agricultural Materials*].

- NR-SAS / SOP 3 (Determination of dry matter and water content on a mass basis). The moisture content of the study material was measured by oven-drying the sample at 105℃ [BS 7755: Section 3.1 (1994)].
- NR-SAS / SOP 5 (Particle size distribution). This was determined by the method of sieving and sedimentation on the mineral fraction of a study material [BS 7755: Section 5.4 (1998)].
- NR-SAS / SOP 15 (Phosphorus soluble in sodium hydrogen carbonate). The study material was treated with a 0.5 mol/l sodium hydrogen carbonate solution at pH 8.5. The extract was then analysed by a spectrometric method [BS 7755: Section 3.6 (1995)].
- NR-SAS / SOP 30 (Determination of ammonium-N, nitrate-N and nitrite-N extracted by potassium chloride). Ammonium-N, nitrate-N and nitrite-N were extracted from soil using a solution of potassium chloride. Ammonium-N in the extract was reacted with phenol and hypochlorite to orm indiphenol blue. The blue colour was measured at 650nm. Nitrate-N in the extract was reduced to nitrite by copper-hydrazine solution. The resultant nitrite and any nitrite in the original extract was reacted with sulpanilamide and N-1-naphthylethylenediamine to form a red azo dye that was measured at 520nm [Method 53 of the MAFF Reference Book RB427 (1986) *Analysis of Agricultural Materials,* „Automated Hydrazine Reduction Method‟, p 4-90, *Standard Methods for the Examination of Water and Wastewater* (19th Edition, 1995) and „Automated Phenate Method‟, p 4-81, *Standard Methods for the Examination of Water and Wastewater* (19th Edition, 1995)].

Table 3.2 Fisher LSD Test for the weighted means of the PSD and chemical characteristics of the soil used

Characteristics	Silt Loam	Sandy Loam	Clay Loam
0.063 - 2.0 (mm)	28.4a	57.1b	34.2c
0.002 - 0.063 (mm)	45.8a	25.0b	29.4c
<0.002 (mm)	25.9a	18.0b	36.4c
pH (1:5 water)	7.0a	7.2b	7.8c
EC (µS cm^{-1})	0.103a	0.335b	0.271c
Olsen-P (mg kg^{-1})	9.3a	47.7b	27.9c
Total-P (mg kg^{-1})	575a	1017b	825c
Extractable - Ammonium-N (mg kg^{-1})	<0.05a	83.0b	1.1c
Extractable Nitrite-N (mg kg^{-1})	<0.05a	0.1a	0.047b
Extractable Nitrate-N(mg kg^{-1})	17.8a	60.2b	31.4c
Organic Matter (%)	5.7a	6.3b	5.0c

*Values followed by a different letter are significantly different ($p<0.05$) following Factorial ANOVA

3.3 Physical and chemical characteristics of the composts

To assess the differences in chemical and physical characteristics of the test composts, six sub-samples (5.0 kg) were randomly collected from the bulk compost samples. These bulk samples were subsequently sub-sampled (10 point composite) and, where applicable, these sub-samples were oven dried at 65oC prior to analysis. For the determination of ammonium-N, nitrate-N and nitrite-N a 10 point composite sub-sampled was stored at 4oC prior to analysis. 65^{o}C prior to analysis. For the determination of ammonium-N, nitrate-N and nitrite-N a 10 point composite sub-sampled was stored at 4^{o}C prior to analysis.

Extractable-P was determined by spectrophotometer (Burkhard Scientific SFA-2000), following the sodium hydrogen carbonate method buffered to pH 8.5 outlined in BS 7755: Section 3.6, (1995) and Total-P determined by FAAS (Flame Atomic Absorption Spectrophotometry) (Perkin Elmer 800 System) following microwave digestion (Anton Paar Multi-wave 3000) in *aqua regia* [US EPA Method 3051 and BS 7755: Section 3.13 (1998)]. Organic matter content

(Loss on Ignition) was measured by dehydrating the sample at 105℃ and then ashing at 450℃ [BS EN 13039:2000].

The determination of ammonium-N (NH_4^+), nitrate-N (NO_3^-) and nitrite-N (NO_2^-) was by potassium chloride extraction**.** Ammonium-N, nitrate-N and nitrite-N were extracted from compost using a solution of potassium chloride. Ammonium-N in the extract was reacted with phenol and hypochlorite to form indiphenol blue. The blue colour was measured at 650nm using an auto-analyser (Burkhard Scientific SFA-2000). Nitrate-N in the extract was reduced to nitrite by copper-hydrazine solution. The resultant nitrite and any nitrite in the original extract was reacted with sulpanilamide and N-1-naphthylethylenediamine to form a red azo dye that was measured at 520nm [Method 53 of the MAFF Reference Book RB427 (1986) *Analysis of Agricultural Materials,* „Automated Hydrazine Reduction Method", p 4-90, *Standard Methods for the Examination of Water and Wastewater* (19th Edition, 1995) and „Automated Phenate Method", p 4-81, *Standard Methods for the Examination of Water and Wastewater* (19th Edition, 1995)].

Compost particle size distribution (PSD) was determined by dry sieving following BSI PAS 100:2005, Annex E (Figure 3.1).

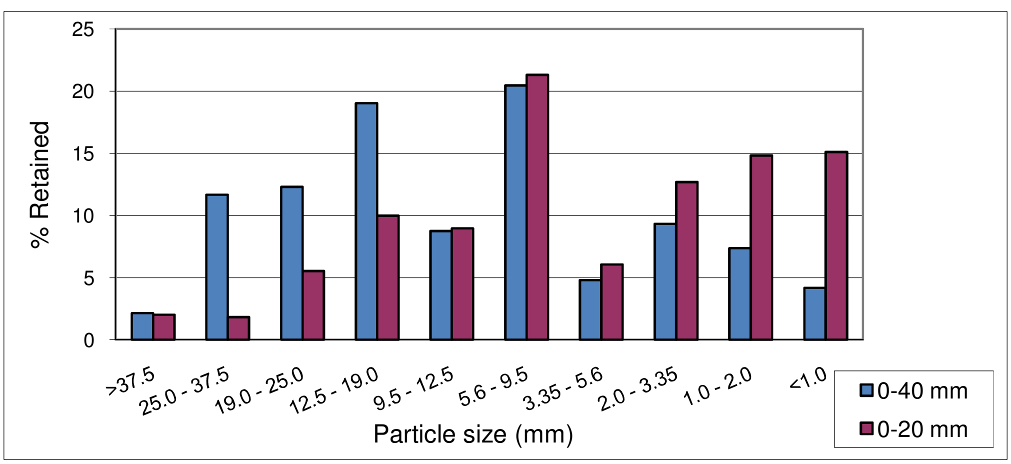


Figure 3.1. Compost PSD 0-20 mm and 0-40 mm

Table 3.3 shows the mean of physical and chemical values of the 2 different composts used in this project. Significant differences were found between the variables evaluated (Table 3.3) by applying the ANOVA Fisher LSD Test ($p < 0.05$).

Table 3.3 Fisher LSD Test for the weighted means of the PSD and chemical characteristics of the two test composts

Parameters	0-40mm Compost	20-40mm Compost
>37.5mm	2.12 a	2.03 a
25.0 - 37.5mm	11.7 a	1.82 b
19.0 - 25.0mm	12.3 a	5.53 b
12.5 - 19.0mm	19.0 a	9.99 b
9.5 - 12.5mm	8.71 a	8.99 a
5.6 - 9.5mm	20.4 a	21.3 a
3.35 - 5.6mm	4.82 a	6.06 b
2.0 - 3.35mm	9.35a	12.7 b
1.0 - 2.0mm	7.43 a	14.8 b
<1.0	4.22a	15.1 b
pH (1:5 water)	8.55 a	8.28b
EC (µS cm^{-1})	3.91 a	3.94 a
Olsen-P (mg kg^{-1})	287 a	308 a
Total-P (mg kg^{-1})	3181 a	3145 a
Extractable Ammonium-N (mg kg^{-1})	86.5 a	14.3 b
Extractable Nitrite-N (mg kg^{-1})	21.3a	1.11 b
Extractable Nitrate-N(mg kg^{-1})	82.9a	305 b
Organic Matter (%)	37.9a	33.2 a

*Means followed by different letters are significantly different ($p < 0.05$) following Fisher LSD Test

3.4 Physical characteristics of ECBs

The ECBs chosen for this research are defined as ECB_{straw} and ECB_{coir}. They are both ECBs currently used for soil erosion control in the UK. They provide full soil coverage. The ECB_{coir} (Type 4K) was provided by ABG Environmental Geosynthetics Ltd (http://www.abg-geosynthetics.com), and is a biodegradable mat, consisting of 100% coir retained by two jute meshes (Figure 3.2a). The technical characteristics of the ECBs are listed in Table 3.4.

Table 3.4. ECBs technical features

Treatment	Mass (g m^{-2})	Max slope	Light penetration (%)	Biodegradability (years)
ECB_{straw}	320	1:1	1.5	2
ECB_{coir}	400	1:1	0	2-5

The ECB_{straw} (ECSC-2) was provided by Geosynthetics Ltd (http://www.geosyn.co.uk), and is made from 70% agricultural straw and 30% coconut fibre uniformly distributed between two polypropylene nets securely sewn together with degradable thread (Figure 3.2b).


a

b

Figure 3.2. Physical appearance of a) ECB_{coir} b) ECB_{straw}

3.5 Soil erosion rig

The experimental programme was conducted using a stainless steel erosion rig, 2.0m x 1.0 m wide and 0.25 m deep (Figure 3.3). The bed of the erosion rig was mounted on a mobile steel frame, which allowed the slope angle to be adjusted at intervals of 5.0º along the transverse axis. A punched steel sheet sat on steel slats 5 cm above the bed of the erosion rig. This was overlain by a permeable fabric (Gardman Weedguard, Performance Weed Control Fabric, 8m x 1.5m) which retained the soil, permitting infiltration and free movement of the leachate towards the leachate collector. Surface runoff was directed towards a funnel-shaped collector at the base of the rig. The collector was covered during simulated rainfall.

Figure 3.3 Stainless steel erosion rig

3.6 Loading and packing the soil into the soil erosion rig

For each soil type, a 10 cm layer of soil of a known mass (kg) was placed above the fabric. For each experiment, all the pre-weighed soil was loaded onto the rig. The soil was manually distributed homogeneously whilst the soil erosion rig was set in a horizontal position.

The soil was subsequently compacted using a 10 kg metal tamper until it reached a 0.1 m^3 volume. To ensure the appropriate soil-rig interface at the base of the rig, a 2.0cm stripe of disaggregated soil (same type) was sprinkled and compacted to avoid excessive infiltration at the interface (Figure 3.4).

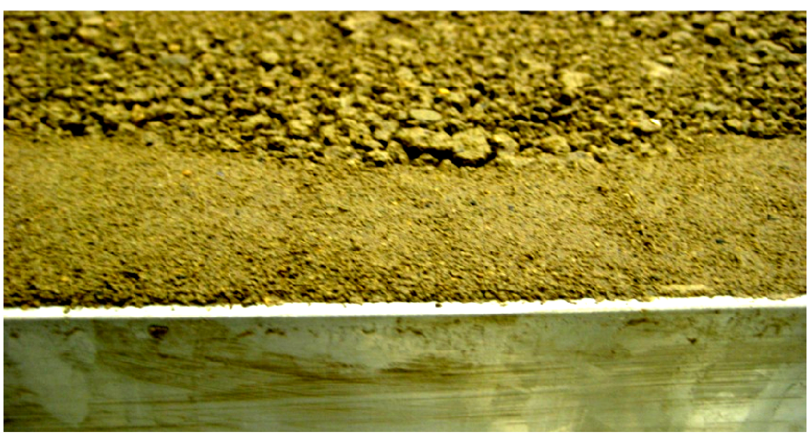


Figure 3.4 Base of soil erosion rig showing the soil runoff collection trough interface

In order to standardize soil compaction, and thus be able to compare the performance of the treatments, the bulk density (BD) was determined for each experiment (Table 3.5). Three randomly selected samples were collected and their bulk density determined, following the methodology applied by Jury and Horton, (2004).

Table 3.5 Mean soil bulk density, standard deviation, standard error and confidence for the experimental soils

Soil type	Mean	Standard Deviation	Standard Error	95% Confidence
Clay	1.1	0.018	0.003	0.013
Silt	1.1	0.023	0.004	0.016
Sand	1.0	0.029	0.005	0.021

It is know that aggregate stability and hence erodibility is affected by the antecedent moisture content of the soil, prior to the onset of rainfall (Morgan, 2005). To reduce the effect of the soil moisture content, the soil was saturated before the experiment using a rainfall event of non-erosive intensity, maintaining the rig in the horizontal position, until steady state leaching was achieved. Subsequently, the soil erosion rig was raised until it reached the right angle for the experiment and the soil was allowed to drain freely for 18-24 hrs before the onset of the experimental rainfall event.

Table 3.6 Soil water content, mean, standard deviation, standard error and confidence

Soil type	Mean (n=18)	Standard Deviation	Standard Error	95% Confidence.
Clay	21.41%	0.007	0.001	0.005
Silt	21.66%	0.008	0.001	0.006
Sand	21.11%	0.013	0.002	0.009

3.7 Preparation and installation of CECBs and ECBs

Six m^3 of compost (3 m^3 of each compost type) was delivered in eight bulk bags and because of its excessive compaction and high moisture content, the compost had formed clods during transport. Consequently, the compost was spread out in a greenhouse facility, and mixed manually every 2 days for 1-

week using a rake, till an adequate structure and moisture content (Figure 3.5a) were reached, namely a friable structure and a moisture content of ≈40% (personal communication Britt Faucette). In order to maintain the achieved characteristics, the compost was subsequently stored in sealed plastic bags till required (Figure 3.5b).


a

b

Figure 3.5 a) spread out compost b) compost storage

For each experiment the compost was manually spread homogeneously over the soil already prepared on the rig, until a uniform depth of 5 cm was achieved.

The ECBs were delivered in two rolls. After inspection, 18 pieces (1.5 x 2.5 m) from each roll were cut, rolled individually and stored in a dark dry place (Figure 3.6a). For each experiment as required a piece of ECB was randomly selected and unrolled over the already prepared soil on the soil erosion rig and cut to match exactly the soil surface. The ECB was fixed to the soil surface with six metal staples following the manufacturer's specifications.


a

b

Figure 3.6 a) ECB preparation b) ECB sampling

3.8 Rainfall simulator

It is generally accepted that climate change will result in significant changes in the amount, frequency, type, intensity and kinetic energy of rainfall experienced in the UK, with an increasing propensity for “heavy” and “extreme” rainfall events (Osborn et al., 2000; Frich et al., 2002; Osborn and Hulme 2000; Christensen et al., 2007; Jenkins, et al., 2007). The changes in the weather do not only concern the frequency of extreme rainfall events but it has been confirmed that seasonal changes have taken place over the same time-span (Osborn et al., 2000, Osborn and Hulme 2000). The precipitation in winter has increased, while the summers have become drier, showing reduced wet day frequencies.

The increase of winter rainfalls has been attributed to the following four causes (Osborn and Hulme, 2002):

- increased amount of precipitation on wet days (daily rainfall >0.4mm d^{-1})
- increased frequency of winter precipitation >15mm d^{-1}
- increased contribution of “heavy” events to winter totals
- increased frequency of “heavy” events with “heavy” precipitation defined as a single daily rainfall total >15 mm d^{-1}

In order to evaluate the performance of CECBs under current and predicted climate change scenarios, the experiment programme was designed to evaluate two rainfall events. The 68mm hr^{-1} 15 minute duration rainfall equates to a 5 year return period storm event and the 68mm hr^{-1} 30 minute duration rainfall simulates a 75 year return period storm event (NERC Flood Studies Report, 1975).

To obtain the required rainfall intensity, a full cone nozzle (460788 Lechler Ltd) was installed on the boom arm of the rain simulator. Calibration of rainfall intensity and homogeneity were undertaken for both experimental slope treatments, namely 2:1 and 3:1 using 110 splash caps. The elevation of the nozzle above the erosion rig and water pressure were adjusted until the target rainfall intensity of 68mm h^{-1} was achieved (Table 3.7).

Table 3.7. Rain simulator calibration parameters

Slope grade	Nozzle height (cm)	Pressure (bar)	Precipitation mean (mm h^{-1})
3:1 slope	210	1.45	69.1± 3
2:1 slope	192	1.45	69.4 ± 3

3.9 Determination of treatment Water Storage (WS).

Previous research (Faucette et al., 2005, 2006, 200, 2009; Glanville et al., 2004; Reinsch et al., 2007; Singer et al., 2006) has indicated that CECBs retain a high proportion of incoming rainfall, thus reducing or eliminating runoff. In order to test this hypothesis it was necessary to determine the experimental water balance (Exp_{WB}).

Where

Rainfall input (ml) = Σ [Runoff (ml) + Leachate (ml) + Soil Water Storage (ml) + Treatment Water Storage (ml)]

To obtain the volume of water for each component of the water balance the following procedure was followed:

- Runoff and leachate were collected and measured every 5 minutes from the start to the end of the event. To determine the treatments' effect on delayed runoff and leachate volume, the last measurement was collected 60 minutes after rainfall cessation.
- The soil total water stored was extrapolated by multiplying the mean water stored (mass percentage of water) obtained from the samples by the mass of the soil loaded into the erosion rigs (kg). The water density was assumed to be 1.0 kg l^{-1}. For each experiment three randomly

selected samples were collected from 0.0-5.0 cm depth before the onset of the experimental storm (post-wetting up and over-night drainage) and 60 mins after cessation of the experimental storm.

- The soil moisture content (mass percent of water) of each sample was calculated following the thermogravimetric method [BS 7755: Section 3.1 (1994)] using a convective oven-drying set at 105^{o}C until a constant weight was achieved. The water stored during the experiment by the samples (percent of water), was determined by the difference between the mean soil water content (mass percent of water) before and after the event.
- The treatment total water stored was extrapolated by multiplying the mean water stored (mass percentage of water) obtained from the treatment samples by the mass of the treatment load (kg). The water density was assumed kg l^{-1}. For each experiment three randomly selected samples were collected from compost load, before the onset of the experimental storm and 60 mins after cessation of the experimental storm.
- The compost moisture content (mass percent of water) of each sample was calculated following the thermogravimetric method [BS 7755: Section 3.1 (1994)], using a convective oven-drying set at 105^{o} C until a constant weight was achieved.
- In order to know the moisture content by using a thermogravimetric method, the ECB was sampled (0.01 x 0.01 m) before and 1 hour after the end of the event in three replicas, then oven dried at 105º C for 24 h. In order to sample without causing disturbance to the treatment, the samples were taken from the edge of the ECBs that were already cut. After the experiment the samples were taken directly from the rig (figure 3.6b).

The initial determination of the Exp_{WB} indicated a systematic positive error (10% positive) in the experimental water, due to the heterogeneity in soil water content between the 0-5.0 cm and 5.0 – 10.0 cm depth. To prove the assumption, from nine control treatments (three for each soil type), three soil samples were randomly collected at both 0-5.0 cm and 5.0 – 10.0 cm depth. The results indicated a small (+1.5 %) but significant difference in soil moisture content between the 0-5.0 cm and 5.0 – 10.0 cm soil depths. As a result the soil storage component of the Exp_{WB} was adjusted and the water balance achieved.

3.10 Environmental condition

To ensure that externalities that may have influenced the experimental programme, the air and water temperature were recorded prior to each experimental replicate. The results indicate that the mean (n=90) air and water temperatures were 18.7 (± 5.0) ^{o}C and 16.6 (± 5.0) ^{o}C.

3.11 Runoff and leachate sampling methodology

For each experimental replicate, the runoff and leachate starting time were recorded and the runoff and leachate discharge measured at 5 minute-intervals, for the duration of the simulated rainfall event. To facilitate the evaluation of treatment performance against the two designed storm events, 3 sub-samples (100 ml each) of leachate and runoff was collected at the end of the 15 minute and 30 minute design storms respectively. One hour after rainfall cessation, the last leachate and runoff volume measurement was taken.

3.12 Determination of Total Suspended Solid (TSS)

Initially it was envisaged that the total soil loss would be determined by multiplying the mean total soil loss of three 100ml sub-samples of collected runoff by the total volume of the runoff collected.

Mass of soil retained on filter paper from a 100ml sub-sample (g l^{-1}) x total runoff volume (l).

The original methodology required that the bulk runoff sample would be agitated for one minute in order to re-suspend the eroded soil and three 100ml sub-samples collected. However, it was observed that the period of time between the agitation of the bulk sample and sub-sample collection, although brief, was sufficient to allow the sedimentation of larger eroded particle size fractions. This was particularly apparent with the silt loam and sandy loam test soils. Consequently, in order to be able to accurately determine the total soil loss, a revised methodology was adopted as follows:

- Filter all runoff samples through 1.00 mm and 63 μm sieves. Measure and record volume (ml). Retain filtered (<63 μm) runoff sample.
- Wash sieves with deionised water and collect > 63μm fraction in a pre-labelled and pre-weighed drying tin. Oven-dry and determine oven-dried weight. Record weight and retain > 63 μm fraction.
- Agitate filtered <63 μm runoff sample retained from Step 1 and collect three 100 ml sub-samples.
- Filter using a vacuum pump and pre-weighed filter paper (45 μm). Determine mass of soil retained on filter paper. Retain supernatant in pre-labelled sample bottles for subsequent determination of ammonium-N, TON (Total Oxides of Nitrogen) and orthophosphate-P in runoff.
- The total soil loss was subsequently determined following the equation: Mass of > 63μm fraction mass of soil retained on filter paper x total runoff volume + mass fraction > 63μm.

3.13 Total nutrients (P and N) mass (mg) load from runoff and leachate.

To quantify the total loss of ammonium-N, TON and orthophosphate-P, dissolved in runoff and leachate, their concentration (mg l^{-1}) was multiplied by the total volume of runoff or leachate collected for each experiment.
The same procedure were followed in order to estimate the total phosphorous bound to the soil particles (SBP) transported through the sediment.

3.14 Statistical analysis

ANOVA (Analysis of Variance) randomized complete block design (RCBD) three factorial were carried out with soil, treatment and slope as factors using STATISTICA software (StatSoft LTD, 2005) Fisher Least Significant Difference (LSD) test of significance was conducted to determine for each dependent variable, which factors were significant ($p<0.05$). Fisher Homogenous group LSD analysis was performed to determine which values belonged to which statistical group, and the magnitude and direction of the observed differences. Before applying the statistical test, data from the experiments were pre-processed by removing outliers. A normal probability distribution of the data set was achieved by transformation of the dataset by different functions such as natural log, log10, square root or Box-Cox.

4 Results

4.1 Preliminary analysis of the 5 years period return storm event (PRSE)

Results of the Factorial ANOVA analysis indicate significant differences in the dependent variables evaluated as a function of soil and treatment factors. Slope angles 2:1 and 3:1 (horizontal:vertical) had no significant effect on the variables tested.

Table 4.1 Factorial ANOVA analysis, LSD Test ($p < 0.05$) of the dependent variables in relation to slope, soil and treatment factors for the 5 year PRSE

Dependent Variables	Factors		
	Slope	Soil	Treat=ment
Time to runoff initiation (min)	No	Yes	Yes
Total runoff volume (ml)	No	Yes	Yes
Mean runoff rate (ml s^{-1})	No	Yes	No
Total leach volume (ml)	No	Yes	Yes
Total suspended solids (TSS) plot (g)	No	Yes	Yes
Total suspended solids (TSS) concentration (g l^{-1})	No	Yes	Yes
Runoff Total Oxides of Nitrogen (TON) concentration (mg l^{-1})	No	Yes	Yes
Runoff total loss of TON per plot (mg $plot^{-1}$)	No	Yes	No
Runoff ammonium-N concentration (NH_4^+) (mg l^{-1})	No	Yes	Yes
Runoff ammonium-N plot (NH_4^+) (mg)	No	Yes	Yes
Runoff orthophosphate-P concentration (mg l^{-1})	No	Yes	Yes
Runoff orthophosphate-P per plot (mg)	No	Yes	Yes
Sediment bound phosphorous (SBP) concentration (mg kg^{-1})	No	Yes	Yes
Sediment bound phosphorous (SBP) per plot (mg)	No	Yes	No
Leachate Total Oxides of Nitrogen (TON) concentration (mg l^{-1})	No	Yes	Yes
Leachate total loss of TON per plot (mg)	No	Yes	Yes
Leachate ammonium-N (NH_4^+) concentration (mg l^{-1})	No	No	No
Leachate ammonium-N (NH_4^+) plot (mg)	No	No	No
Leachate orthophosphate-P concentration (mg l^{-1})	No	Yes	Yes
Leachate orthophosphate-P per plot (mg)	No	Yes	Yes

The soil slope did not affect the performance of any treatment, thus that factor is not taken into account for both the 15 and 30 min storm event in the following analysis.

The initial chemical analysis undertaken on the runoff and leachate samples also involved the determination of both NO_2^- and NO_3^-, thus distinguishing the two different forms of N.

However, after the first experimental replicates, the values detected for NO_2^- were constantly 4 orders of magnitude smaller than NO_3^-. Consequently, to save time and project costs, NO_2^- analysis was stopped and TON determined and assumed to be representative of NO_3^-.

4.2 Treatment performances on silt loam soil

Following factorial ANOVA, the Fisher LSD Test ($p < 0.05$) was applied to the runoff and soil loss performance indicators listed in Table 4.2, in relation to the different treatments applied. The weighted means were calculated using un-transformed values. Homogeneous groups ($p < 0.05$) were generated from data normalized using a mathematical transformation of the real data.

Table 4.2 Fisher LSD Test for 5 years PRSE for the weighted means of the runoff and soil loss performance indicators for all treatments tested on silt loam soil

Treatment	Runoff start time (min)	Runoff volume (ml)	Runoff rate ($ml\ s^{-1}$)	Leachate volume (ml)	TSS mass (g)	TSS conc ($g\ l^{-1}$)
$CECB_{0-20}$	9.9 a	81 ab	0.17 a	3705 c	0.8 a	0.57 bc
$CECB_{0-40}$	14.3 a	72 b	0.41 a	1912 b	0.12 a	0.89 c
ECB_{straw}	3.25 c	138 a	0.19 a	12778 a	0.01 a	0.08 a
ECB_{coir}	3.9 c	196 a	0.28 a	12529 a	0 a	0.05 a
Control	6.08 ab	57 ab	0.09 a	19135 a	0.14 a	0.64 b

*Means followed by different letters are significantly different ($p < 0.05$) following Fisher LSD test

4.2.1 Runoff initiation time

The Fisher LSD Test results indicate that for runoff initiation time (min), using the natural logarithm (ln) transformed values, runoff started first on ECBs, followed by the control and then CECBs. No significant differences were found between ECB_{straw} and $ECB_{coir,}$ treatments. However, these varied significantly from the $CECB_{0-20mm}$ and $CECB_{0-40mm}$ treatments (Figure 4.1).

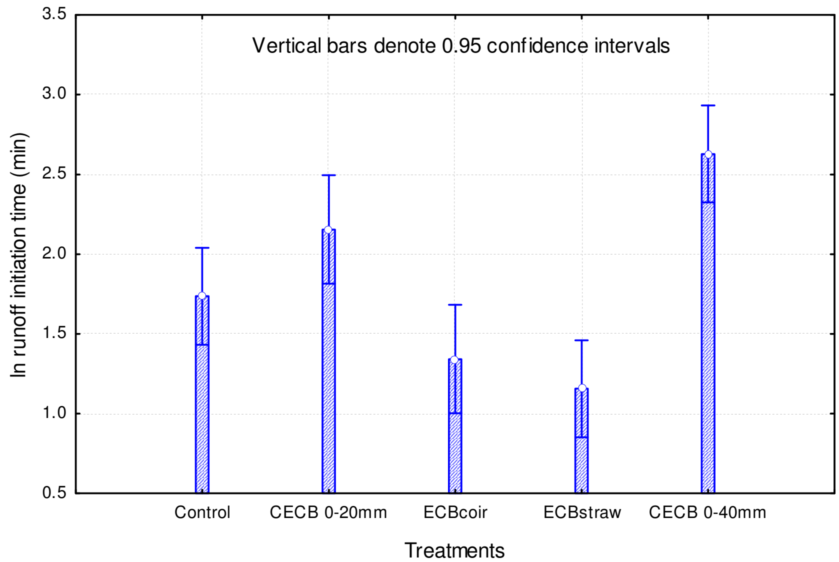


Figure 4.1 Silt loam soil: Effect of treatments on runoff initiation time (min) using ln transformed values following Fisher LSD Test

4.2.2 Runoff volume and rate

The Fisher LSD Test ($p < 0.05$) for runoff volume (ml) and rate (ml s^{-1}), using logarithm base 10 (log 10) and by ln transformed values respectively, demonstrated that the $CECB_{0\text{-}40mm}$ treatment generated significantly less runoff volume (ml) than the ECBs but did not vary significantly from the $CECB_{0\text{-}20mm}$ and control treatments (Figure 4.2 and Table 4.2). In contrast, no significant difference in runoff rate (ml s^{-1}) was observed between treatments (for brevity, figure not shown).

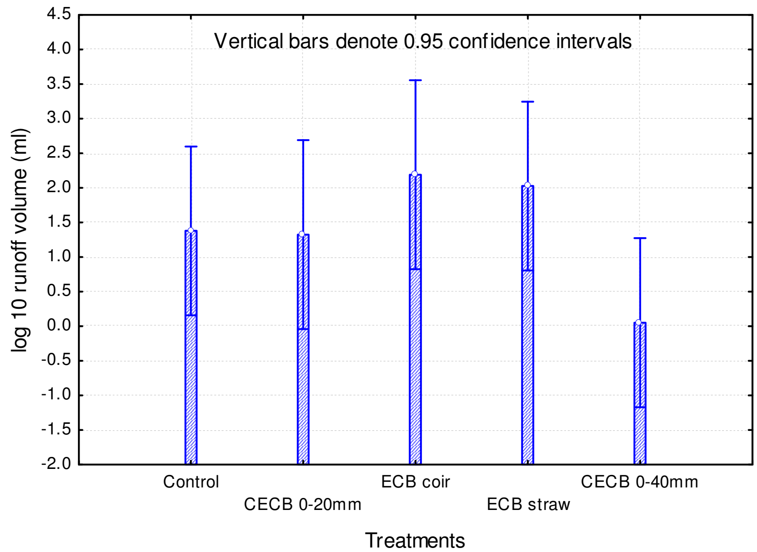


Figure 4.2 Silt loam soil: Effect of treatments on runoff total volume (ml) (log 10 transformed data)

4.2.3 Leachate volume

For the treatments tested the results of the Fisher LSD Test ($p < 0.05$) indicate that leachate volume (ml) was significantly greater from the ECBs and control as compared with both the CECBs treatments. Further, the $CECB_{0\text{-}40mm}$ generated significantly less leachate as compared with all the other treatments (Table 4.2) (for brevity, figure not shown).

4.2.4 Total Suspended Solid (TSS) concentration and total loss of soil per plot

Following the Fisher LSD Test ($p < 0.05$), using ln transformed values for total suspended solid (TSS), load (g) and concentration (g l^{-1}), no significant differences were found between treatments with regards TSS load (g). However, the concentration of TSS (g l^{-1}) was significantly lower from both the ECBs treatments as compared with the control and CECBs. CECB0-40mm showed the highest TSS concentration (Figure 4.3). TSS generated by the CECBs after a visual inspection, appeared mostly to be constituted by organic particles. Its colour was darker than the TSS produced from the other treatments, which could have been partly generated by the compost rather than the soil.

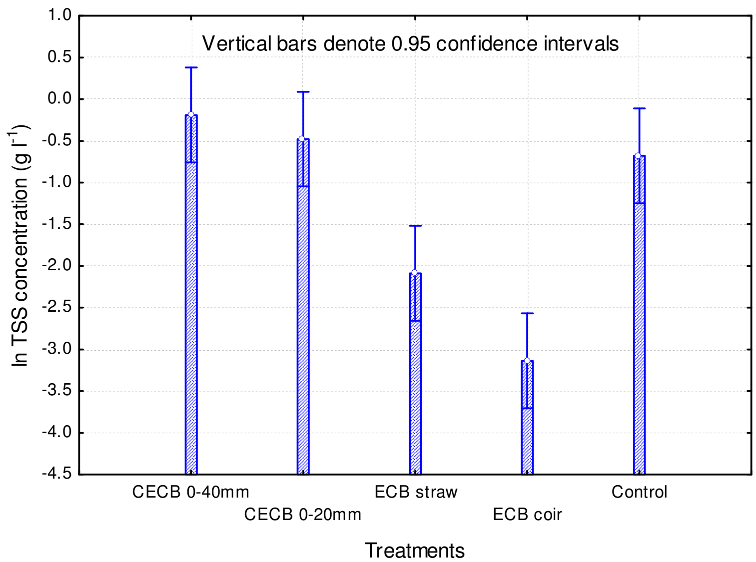


Figure 4.3 Silt loam soil: ln transformed values for TSS concentration (g l^{-1}) for all treatments

4.2.5 Chemical analysis of runoff and leachate

The Fisher LSD Test (p <0.05) was applied to the runoff and leachate quality indicators listed in Table 4.3 and 4.4. The weighted means in Table 4.3 and 4.4 were calculated from the un-transformed data. Homogeneous groups (p <0.05) were generated from data normalized following a mathematical transformation.

Table 4.3 Fisher LSD Test for 5 years PRSE for the weighted means of the runoff quality indicators, for all treatments tested on silt loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)	P-bound plot (mg)	P-bound conc (mg kg^{-1})
$CECB_{0-20}$	0.0 a	0.21 a	23.1 a	11.6 a	0.0 ab	0.21 a	5.16 a	106 ab
$CECB_{0-40}$	0.3 a	0.35 a	127 a	94.4 a	0.8 a	0.28 a	8.8 a	151 a
ECB_{straw}	0.0 a	0.11 a	0.0 a	0.13 a	0.1 ab	0.0 a	6.65 a	370 bc
ECB_{coir}	0.0 ab	0.4 a	0.8 a	0.45 a	0.0 b	0.19 b	1.94 a	127 ab
Control	0.1 b	0.0 b	4.5 a	3.81 a	0.1 a	0.0 a	0.32 a	213 c

*Means followed by different letters are significantly different (p < 0.05)

Table 4.4 Fisher LSD Test for 5 years PRSE for the weighted means of the leachate quality indicators, for all treatments tested on silt loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)
$CECB_{0-20}$	0.22 a	0.83 a	99.8 a	386 ab	0.25 a	0.86 a
$CECB_{0-40}$	2.16 a	4.61 a	93.8 ab	196 b	0.25 a	0.5 a
ECB_{straw}	0.12 a	1.68 a	85.2 ab	1085 a	0.05 a	0.57 a
ECB_{coir}	0.22 a	2.66 a	92.1 ab	1090 a	0.19 a	2.17 a
$€Control	0.05 a	1.09 a	41.5 b	835 a	0.04 a	0.85 a

*Means followed by different letters are significantly different (p < 0.05)

4.2.6 Runoff ammonium-N concentration and total mass of ammonium-N lost per plot

The Fisher LSD Test (p <0.05), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and ammonium-N lost from the plot (mg), indicated that the control generated the lowest concentration and the lowest ammonium-N load plot (mg). In all cases, irrespective of treatment, extremely low values of ammonium-N concentration (mg l^{-1}) often below detection limits of auto analyser were detected. Consequently no contamination hazard ammonium-N will result from the CECBs use.

4.2.7 Total Oxides Nitrogen (TON) concentration in runoff and total loss of TON per plot

In similarity to the results observed with ammonium-N, no significant differences were found between the treatments in relation to the Box Cox transformed values for TON concentration (mg l^{-1}) and total loss of TON per plot (mg) following Fisher LSD Test (p <0.05). This is in large part due to the high degree of variability within and between treatments. The trend is for higher concentrations of TON (mg l^{-1}) from CECB treatments although this trend is not significant (Figure 4.4). The concentrations of Nitrate-N in the $CECB_{0-20}$ and $CECB_{0-40}$ were significantly different (Table 4.3), with mean (n=6) values of 306 and 83.0 mg kg^{-1} respectively. However, no significant differences were observed between the $CECB_{0\text{-}20}$ and $CECB_{0\text{-}40}$ in terms of concentrations of TON in runoff or total loss of TON per plot (mg) (Table 4.2).

4.2.8 Runoff orthophosphate-P concentration and total loss of orthophosphate-P per plot.

Fisher LSD Test ($p < 0.05$), performed on Box Cox transformed data, indicates that levels of orthophosphate-P were extremely low with mean values for all treatments ranging from 0.00 to 0.8 mg l^{-1} (Table 4.2). Consequently, the mean total loss of orthophosphate-P from the treatments tested was in all cases <0.3 mg per plot (Figure 4.4). The results also indicate that although the concentrations of extractable-P in the $CECB_{0\text{-}20}$ and $CECB_{0\text{-}40}$ were 308 and 287 mg kg^{-1}, respectively which equates to approximately 24,640 and 22,960 mg of extractable-P per plot, the orthophosphate-P values were well below the EU maximum permissible levels.

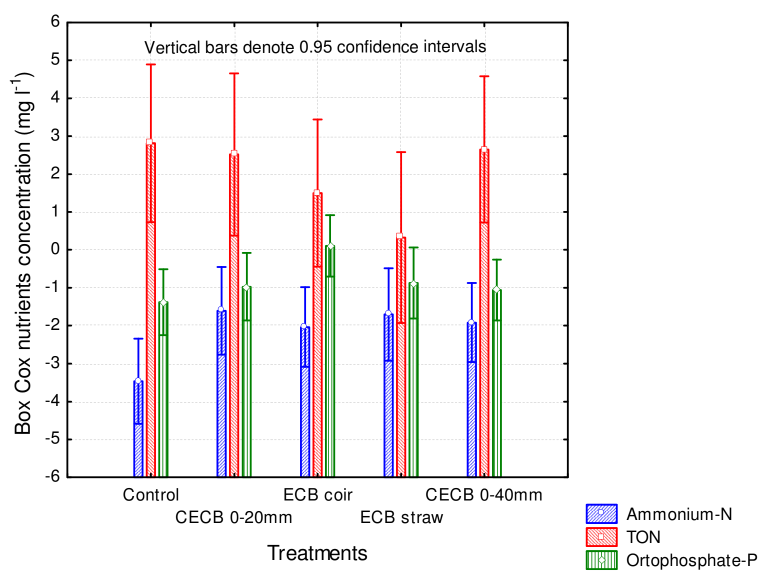


Figure 4.4 Silt loam soil: Total loss of ammonium-N, TON and orthophosphate-P per concentration (mg l^{-1}) in runoff (Box Cox transformed values)

4.2.9 Total Sediment Bound Phosphorous (SBP) concentration and total loss of SBP per plot

The Fisher LSD Test ($p < 0.05$) was applied to the Box Cox transformed values for the total loss of SBP per plot (mg), and to SQRT transformed values for the SBP concentration (mg kg^{-1}). The results indicate that the SBP concentration (mg l^{-1}) was significantly higher from the control and ECB_{straw} as compared with all the other treatments (Figure 4.5). With regards total loss of SBP per plot (mg), no significant differences were observed between treatments.

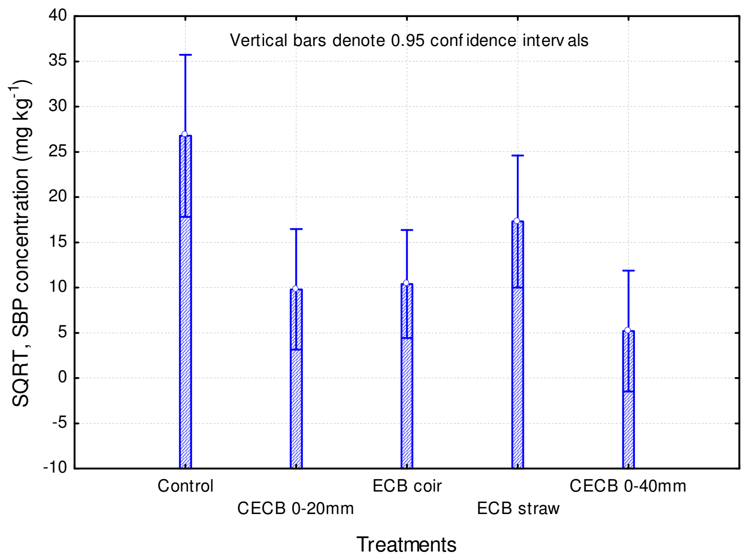


Figure 4.5 Silt loam soil: Effect of treatment on SBP concentration (mg kg^{-1}) in runoff (SQRT transformed values)

4.2.10 Leachate ammonium-N concentration and total mass of ammonium-N lost per plot

The Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-}) and ammonium-N lost per plot (mg), indicated that there is no significant difference between the treatments. Furthermore extremely low values, often below detection limits of auto analyser for all the treatments were detected (Table 4.3).

Therefore, also in relation to the leachate produced from CECBs, there is no ammonium-N contamination risk.

4.2.11 Leachate TON concentration and total loss of TON per plot

Significant differences were found between treatments in relation to the Box Cox transformed values for TON concentration (mg l^{-1}) and total loss of TON per plot (mg) following Fisher LSD Test ($p < 0.05$).The trend is for higher concentrations of TON (mg l^{-1}) in leachate from CECBs treatments although this trend is significant only for CECB0-20mm. Due to the reduced volume of leachate, generated from CECBs compared to the other treatments the total TON loss, values were significantly lower (approximately 3 times) for CECBs.

4.2.12 Leachate orthophosphate-P concentration and total loss of orthophosphate-P per plot

Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicates that levels of orthophosphate-P in leachate were extremely low with mean values for all treatments ranging from 0.04 to 0.25 mg l^{-1} (Table 4.3). Consequently, the mean total loss of orthophosphate-P from the treatments tested was in all cases < 2.17 mg per plot. The pollution hazard caused by CECBs will be not an issue, since the water quality standard indicators for the UK, relative to the soluble-P concentration (mg l^{-1}) in rivers, are two orders of magnitude greater than the concentration of orthophosphate-P detected in the CECBs leachate.

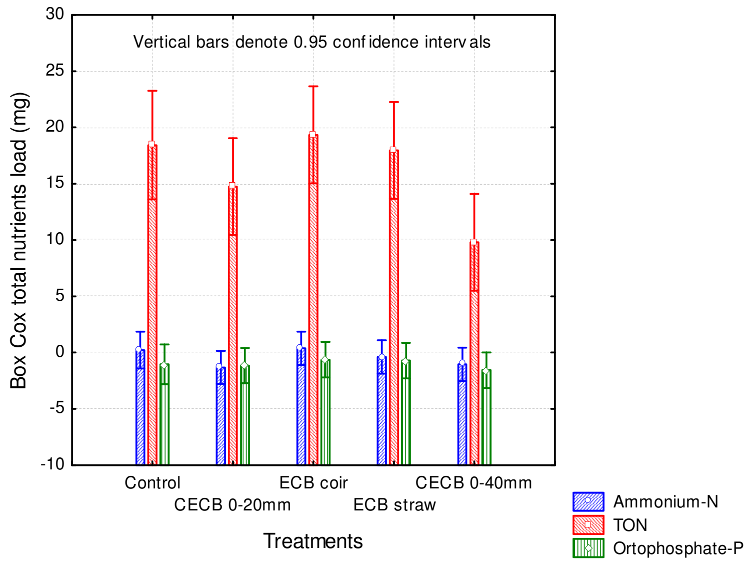


Figure 4.6 Silt loam soil: Total loss of ammonium-N, TON and orthophosphate-P per concentration (mg l^{-1}) in leachate (Box Cox transformed values)

4.3 Treatment performances on sandy loam soil

Following factorial ANOVA, the Fisher LSD Test ($p < 0.05$) was applied to the runoff and soil loss performance indicators listed in Table 4.1, in relation to the different treatments applied. The weighted means in Table 4.4 were calculated using un-transformed values. Homogeneous groups ($p < 0.05$) were generated from data normalized using a mathematical transformation of the real data.

Table 4.5 Fisher LSD Test for 5 years PRSE for the weighted means of the runoff and soil loss performance indicators for all treatments tested on sandy loam soil

Treatment	Runoff start time (min)	Runoff volume (ml)	Runoff rate (ml s^{-1})	Leachate volume (ml)	TSS mass (g)	TSS conc (g l^{-1})
$CECB_{0-20}$	18.3 a	77 a	0.14 b	2370 a	0.02 a	0.13 a
$CECB_{0-40}$	18.6 a	15 ab	0.02 b	1811 a	0.01 a	0.43 a
ECB_{straw}	3.42 b	141 c	0.21 a	9709 b	0.00 a	0.04 a
ECB_{coir}	3.22 b	219 c	0.31 a	11813 bc	0.02 a	0.09 a
Control	5.45 b	48 bc	0.08 a	16627 c	0.06 a	0.47 a

*Means followed by different letters are significantly different ($p < 0.05$) following Fisher LSD Test

4.3.1 Runoff initiation time

The Fisher LSD Test ($p < 0.05$) for the runoff initiation time (min), using the ln transformed values (Table 4.4), demonstrated for both, $CECB_{0\text{-}20}$ and $CECB_{0\text{-}40}$ treatments, that the runoff started significantly later. On CECBs runoff started 5 times later than ECBs and 3 times later than with control (Figure 4.7).

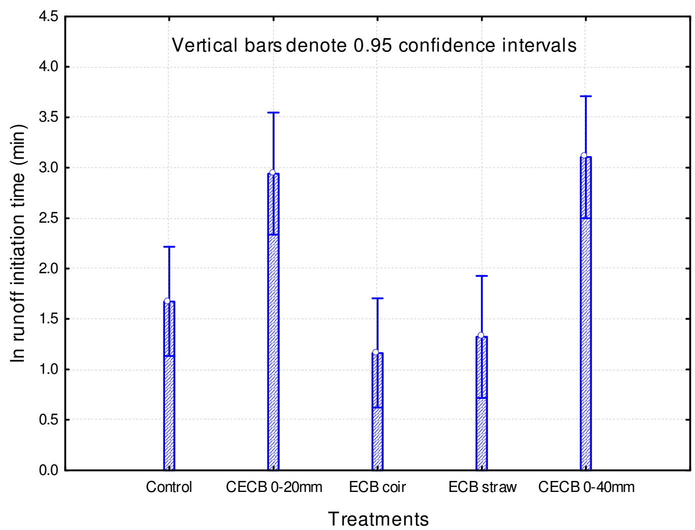


Figure 4.7 Sandy Loam Soil: Effect of treatments on runoff initiation time (min) using ln transformed values following Fisher LSD Test

4.3.2 Runoff volume and runoff rate

The Fisher LSD Test ($p < 0.05$) for runoff volume (ml) and rate ($ml\ s^{-1}$), using respectively log 10 and ln transformed values (Table 4.7), demonstrated that CECBs generate significantly less (more than 50% less) runoff volume than ECBs (Figure 4.8). Control shows intermediate values, comparable with CECB0-40mm and ECBs. With regards to the runoff rate, significantly lower values (approximately 50%) were associated with CECBs as compared with ECBs (Figure 4.9).

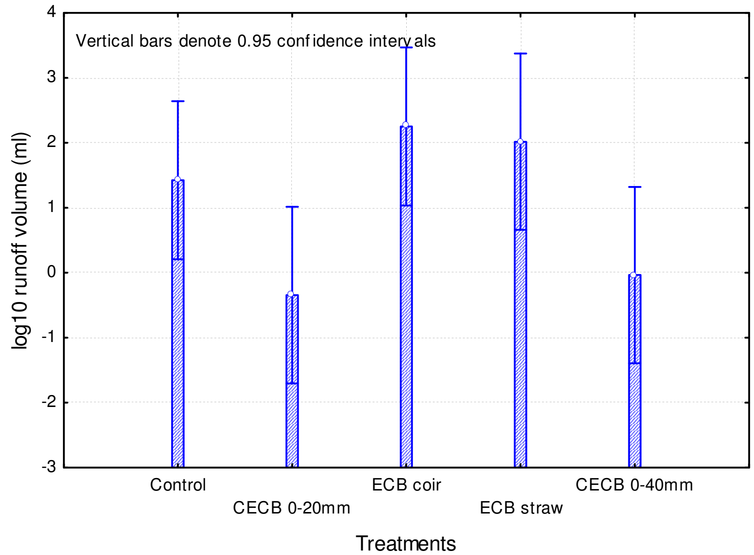


Figure 4.8 Sandy loam soil: Effect of treatments on runoff total volume (ml) (log 10 transformed data)

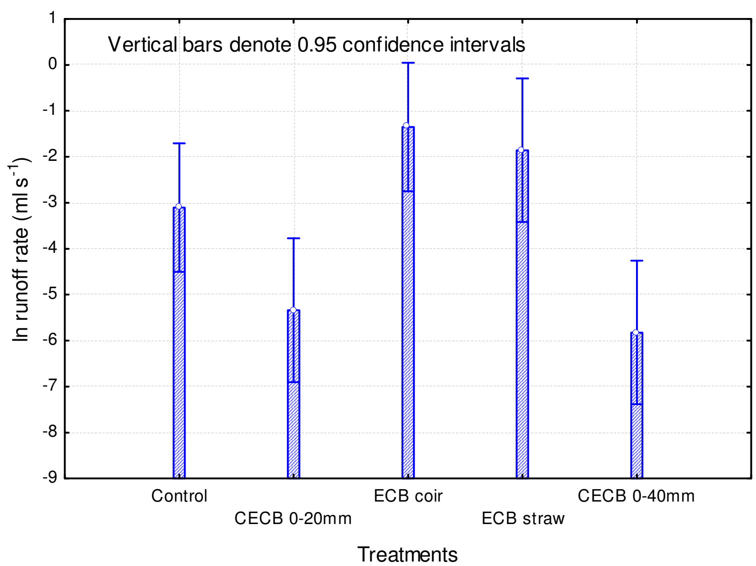


Figure 4.9 Sandy loam soil: Effect of treatments on runoff rate (ml s^{-1}) ln transformed data

4.3.3 Leachate volume

Results of the Fisher LSD Test ($p < 0.05$) applied to ln transformed values follows a similar trend to runoff volume (ml) with significantly lower leachate volumes (ml) associated with the CECB0-20mm and CECB0-40mm treatments as compared with the ECBs and control. Leachate volume (ml) was in the order Control > ECB_{coir} = ECB_{straw} > CECB0-20mm = CECB0-40mm.Total leachate volume (ml) generated from CECBs was 5 times less as compared with the volume (ml) generated from ECBs (Figure 4.10).

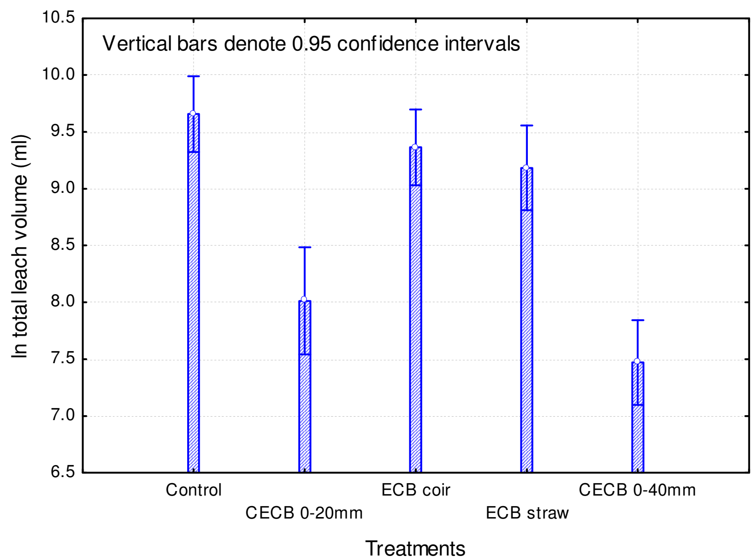


Figure 4.10 Sandy loam soil: ln transformed values for leach total volume (ml) for all treatments

4.3.4 Total Suspended Solid (TSS) concentration and total loss of soil per plot

Following the Fisher LSD Test ($p < 0.05$), using ln transformed values for TSS load (g) and concentration (g l^{-1}), no significant differences were found between the treatments with regards TSS load per plot (g). However, the concentration of TSS (g l^{-1}) was significantly lower from ECB_{straw} treatments as compared with the control and CECB treatments. ECB_{coir} generated the highest TSS total load plot (g) values (Figure 4.11). Since TSS generated from CECBs appeared visually dark and apparently rich in organic matter, it is most likely that TSS load from CECBs contained particles eroded also from the CECB.

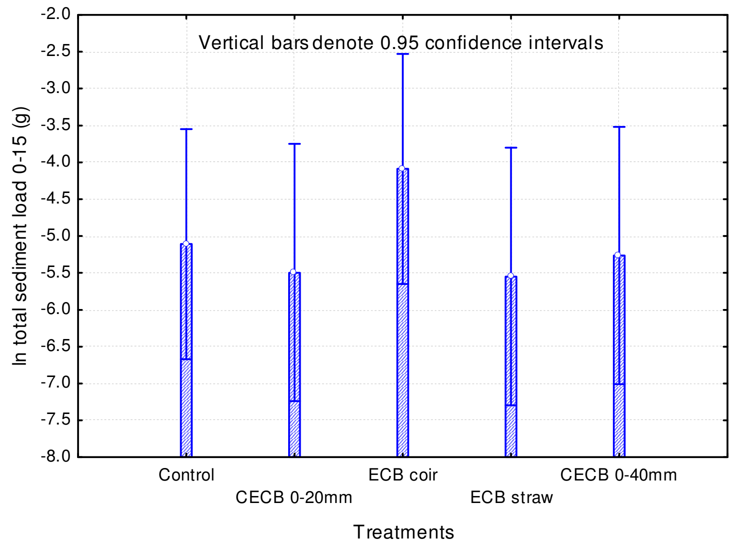


Figure 4.11 Sandy loam soil: ln transformed values for TSS total load per plot (g) for all treatments

4.3.5 Chemical analysis of runoff and leachate

The Fisher LSD Test ($p < 0.05$) was applied to the runoff and leachate quality indicators listed in Table 4.5 and 4.6. The weighted means in Table 4.5 and 4.6 were calculated from the un-transformed data. Homogeneous groups ($p < 0.05$) were generated from data normalized following a mathematical transformation.

Table 4.6 Fisher LSD Test for 5 years PRSE for the weighted means of the runoff quality indicators, for all treatments tested on sandy loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)	P-bound plot (mg)	P-bound conc (mg kg^{-1})
$CECB_{0-20}$	1.00 a	0.37 a	48.8 a	18.0 a	1.14 a	0.43 ab	1.21 a	98.2 a
$CECB_{0-40}$	0.37 a	0.01 a	85.5 a	1.67 a	1.05 a	0.03 a	3.25 a	205 ab
ECB_{straw}	0.65 a	0.05 a	8.41 ab	12.8 a	1.08 a	0.19 ab	12.60 a	361b
ECB_{coir}	0.37 a	0.08 a	63.0 ab	15.5 a	1.60 a	0.34 b	1.34 a	99.8 ab
Control	0.17 a	0.02 a	62.4 b	1.24 a	0.47 a	0.02 a	3.10 a	102 ab

*Means followed by different letters are significantly different ($p < 0.05$)

Table 4.7 Fisher LSD Test for 5 years PRSE for the weighted means of the leachate quality indicators, for all treatments tested on sandy loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)
$CECB_{0-20}$	0.16 a	0.65 a	223.3 a	696 a	0.23 ab	0.58 a
$CECB_{0-40}$	0.38 a	0.74 a	247.6 a	460 a	0.44 a	0.83 a
ECB_{straw}	0.15 a	1.53 a	165.3 a	1576 ab	0.07bc	0.73 a
ECB_{coir}	0.23 a	2.75 a	187.3 a	2122 ab	0.03c	0.34 a
Control	0.13 a	2.1 a	174.2 a	3332 b	0.11abc	1.88 a

*Means followed by different letters are significantly different ($p < 0.05$)

4.3.6 Runoff ammonium-N concentration and total mass of ammonium-N loss per plot

The Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and ammonium-N loss from the plot (mg), indicated that the control treatments generated the lowest concentration and the lowest ammonium-N load per plot (mg) (Table 4.5). Extremely low values, often below detection limits of auto analyser, were detected for all the treatments.

4.3.7 Runoff Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

No significant differences were found between the treatments in relation to the Box Cox transformed values of total loss of TON per plot (mg) following Fisher LSD Test ($p < 0.05$). However, TON concentrations (mg l^{-1}) were significantly higher for CECBs.

The concentrations of Nitrate-N in the $CECB_{0-20}$ and $CECB_{0-40}$ were significantly different (Table 3.3) with mean (n=6) values of 306 and 83.0 mg kg^{-1}, respectively. However, no significant difference occurred between CECBs. According to the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008), to consider fresh water unpolluted, the concentration of nitrate has to be less than 50 mg l^{-1}. Even though the TON concentrations of all treatments are not far from that limit, only ECB_{straw} and CECB0-20mm generated runoff with nitrate levels lower than the limit.

4.3.8 Runoff orthophosphate-P concentration and total loss of orthophosphate-P per plot

The Fisher LSD Test ($p < 0.05$), performed on Box Cox transformed data, indicated no significant differences between the treatments in relation to the orthophosphate-P concentration (mg l^{-1}). Although the concentrations of Total-P (mg kg^{-1}) in the CECB0-20mm and CECB0-40mm compost were 3145 and 3181 mg kg^{-1} respectively for all treatments on sandy loam soils, the orthophosphate-P concentration in the runoff was below the limits permitted by the UK water quality standard (Tables 2.5 and 2.6). This suggests that the fraction of water soluble P in the compost must be minimal. The total orthophosphate-P load plot (mg) was significantly higher on ECB_{coir} as compared with CECB0-40mm because the ECB_{straw} generated a significantly higher runoff volume (Figure 4.12).

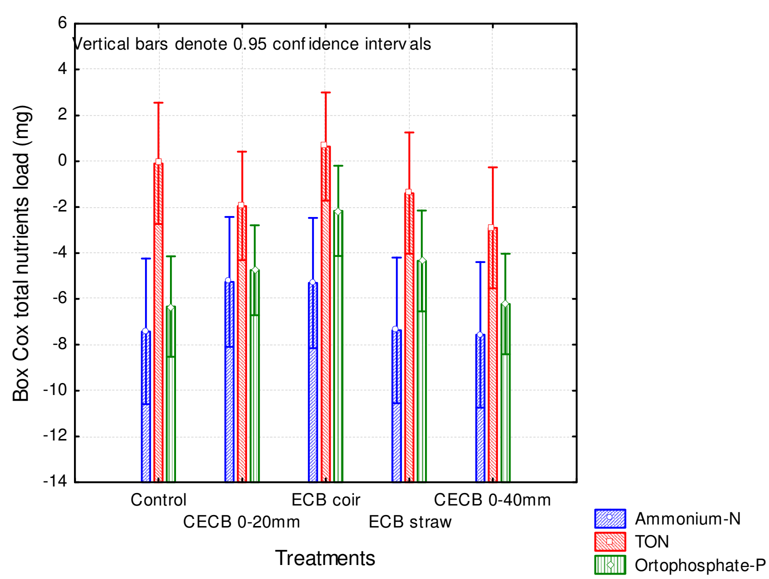


Figure 4.12 Sandy loam soil: Total loss of ammonium-N, TON and orthophosphate-P per plot (mg) in runoff (Box Cox transformed values)

4.3.9 Total Sediment Bound Phosphorous (SBP) concentration and total loss of SBP per plot

The Fisher LSD Test ($p < 0.05$) was applied to the Box Cox transformed values for the total loss of SBP per plot (mg), and to SQRT transformed values for the SBP concentration (mg Kg^{-1}). The results indicated that the SBP concentration (mg l^{-1}) was significantly higher from the ECB_{straw} as compared with CECB0-20mm (Table 4.5). With regards to the total loss of SBP per plot (mg), no significant differences were observed between treatments (Figure 4.13). Total SBP concentration (mg kg^{-1}) in runoff was significantly higher from the sandy loam soil, as compared to the silt loam soil, due the significantly high total-P and extractable-P concentration (mg kg^{-1}) associated with the sandy loam soil.

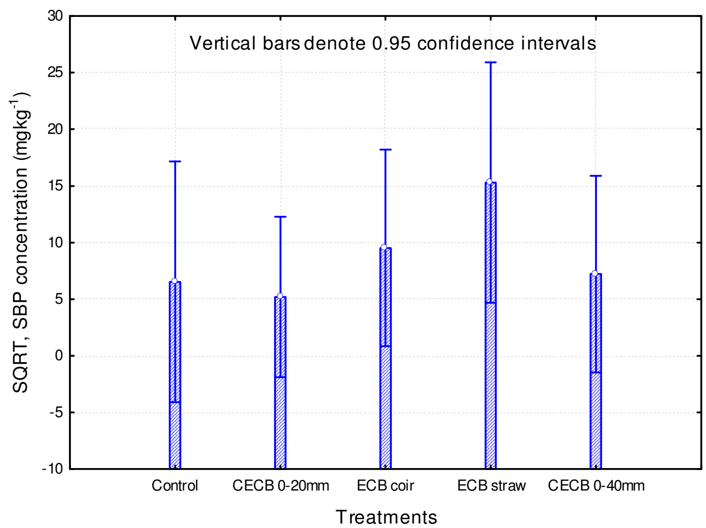


Figure 4.13 Sandy loam soil: Effect of treatment on SBP concentration in runoff (SQRT transformed values)

4.3.10 Leachate ammonium-N concentration and total mass of ammonium-N lost from plot

The Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and ammonium-N lost from the plot (mg), indicated that there is no significant difference between the treatments.

Furthermore, extremely low values, often below detection limits of auto analyser, were detected for all the treatments. All of the treatments generated leachate ammonium-N concentration values lower than the limits (>50 mg l^{-1}) permitted by the UK Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008)

4.3.11 Leachate TON concentration and total loss of TON per plot

No significant differences were found between the treatments in relation to the Box Cox transformed values for TON concentration (mg l^{-1}) in leachate following the Fisher LSD Test ($p < 0.05$). Total losses of TON per plot (mg) values were significantly lower for CECBs as compared with the control. Similar to the silt loam soil treatments, the trend is for higher concentrations of TON (mg l^{-1}) from CECBs treatments although this trend is not significant. Nevertheless due to the reduced volume of leachate generated from CECBs, compared to the other treatments the total TON loss (mg) values were significantly lower for CECBs (60%).

4.3.12 Leachate orthophosphate-P concentration and total loss of orthophosphate-P per plot

The Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicated that concentrations (mg l^{-1}) of orthophosphate-P were significantly higher for CECBs as compared to the other treatments (3 time). However, because CECBs generated less leachate volume (ml), than all the other treatments, the total loss of orthophosphate was comparable.
Table 4.6 shows the extremely low orthophosphate-P concentrations in leachate with mean values for all treatments ranging from 0.03 to 0.44 mg l^{-1}. Consequently, the mean total loss of orthophosphate-P from the treatments tested was in all cases <1.88 mg per plot. For all treatments the orthophosphate-P concentration in leachate was below the limits permitted for the UK water quality standards for rivers (Tables 2.5 and 2.6).

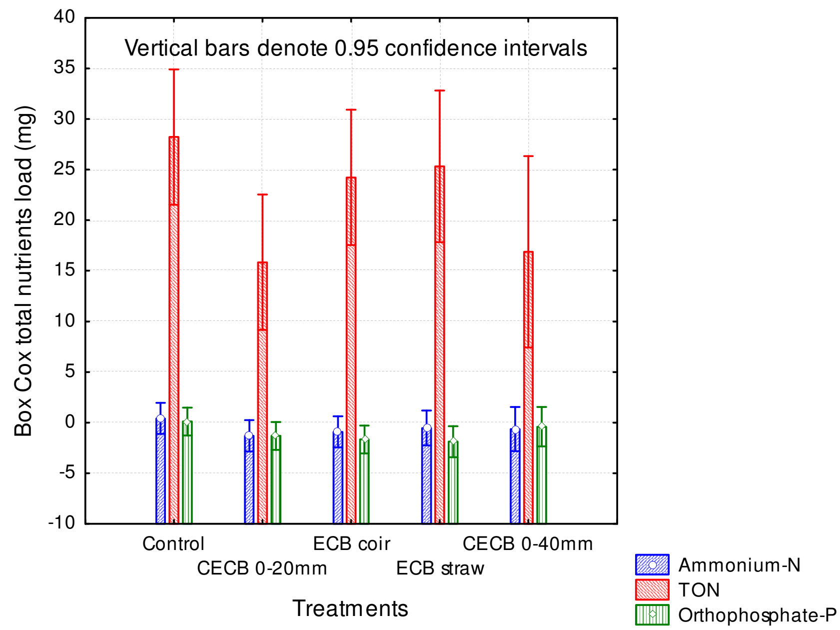


Figure 4.14 Sandy loam soil: Total loss of ammonium-N, TON and orthophosphate-P per concentration in leachate (Box Cox transformed values).

4.4 Treatment performances on clay loam soils

Following factorial ANOVA, the Fisher LSD Test ($p < 0.05$) was applied to the runoff and soil loss performance indicators listed in Table 4.4, in relation to the different treatments applied. The weighted means in Table 4.4 were calculated using un-transformed values. Homogeneous groups ($p < 0.05$) were generated from data normalized using a mathematical transformation of the real data.

Table 4.8 Fisher LSD Test for 5 years PRSE for the weighted means of the runoff and soil loss performance indicators on sandy loam soil

Treatment	Runoff start time (min)	Runoff volume (ml)	Runoff rate (ml s^{-1})	Leachate volume (ml)	TSS mass (g)	TSS conc (g l^{-1})
$CECB_{0-20}$	11 c	105 a	0.39 ab	2981 c	0.1 ac	0.87 ac
$CECB_{0-40}$	12.2 c	432 ab	1.99c	1750 b	0.59 a	1.3 a
ECB_{straw}	4.1 ab	89 ab	0.14 a	12224 a	0.01 b	0.09 b
ECB_{coir}	3.29 a	249 ab	0.36 ab	11739 a	0.09 bc	0.02 bc
Control	4.48 b	579 b	0.86 bc	17776 a	3.23 a	2. a

*Means followed by different letters are significantly different ($p < 0.05$) following Fisher LSD Test

4.4.1 Runoff initiation time

The Fisher LSD Test (p <0.05) for the runoff initiation time (min), using the In transformed values (Table 4.8), demonstrated that for both the $CECB_{0\text{-}20}$ and $CECB_{0\text{-}40}$ treatments, runoff started significantly later as compared with all other treatments. Due to their high WSC, on CECBs the runoff started approximately 3 times later than all the other treatments (Figure 4.15).

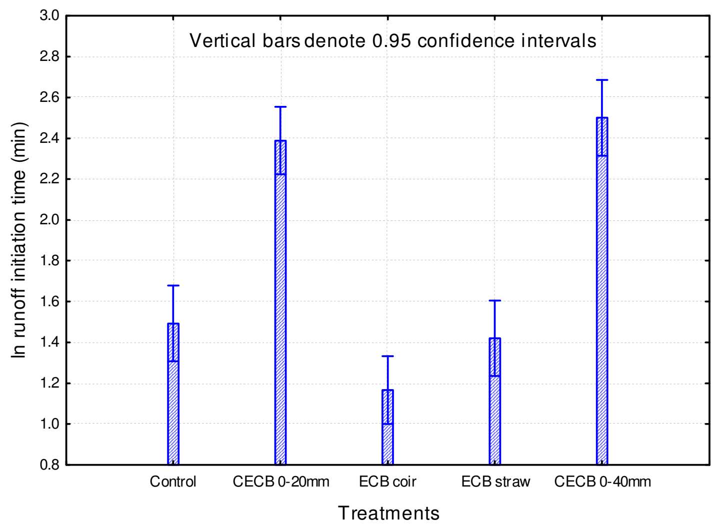


Figure 4.15 Clay Loam Soil: Effect of treatments on runoff initiation time (min) using In transformed values following Fisher LSD test.

4.4.2 Runoff volume and rate

The Fisher LSD Test (p <0.05) for runoff volume (ml) and rate (ml s^{-1}), using respectively by log 10 and In transformed values (Table 4.4), demonstrated that CECB0-20mm generated significant less runoff volume (ml) than the control (Figure 4.16). All the other treatments showed intermediate values. In contrast to the sandy loam and silt loam soil treatments, runoff rate (ml s^{-1}) was significantly higher on the CECB0-40mm as compared with CECB0-20mm and ECBs treatments. Control showed intermediate values. Due to its reduced hydraulic conductivity, on clay all the treatments generated more runoff volume (ml) than on sandy loam and silt loam soils. CECB0-40mm is the treatment that was most strongly affected by the soil type.

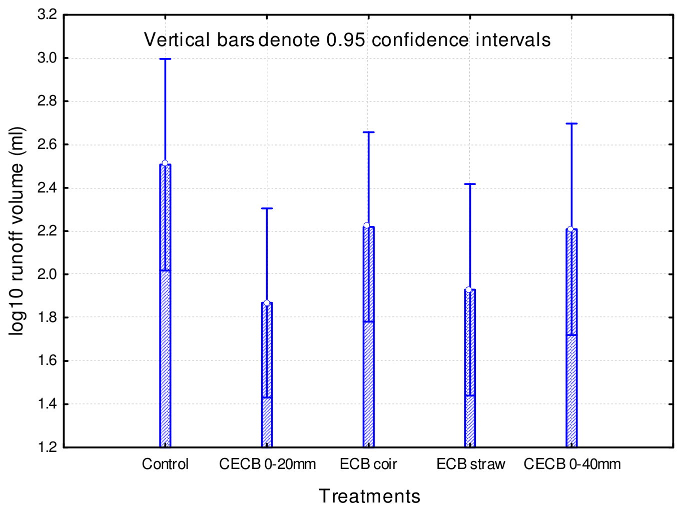


Figure 4.16 Clay loam soil: Effect of treatments on runoff total volume (ml) (log 10 transformed data)

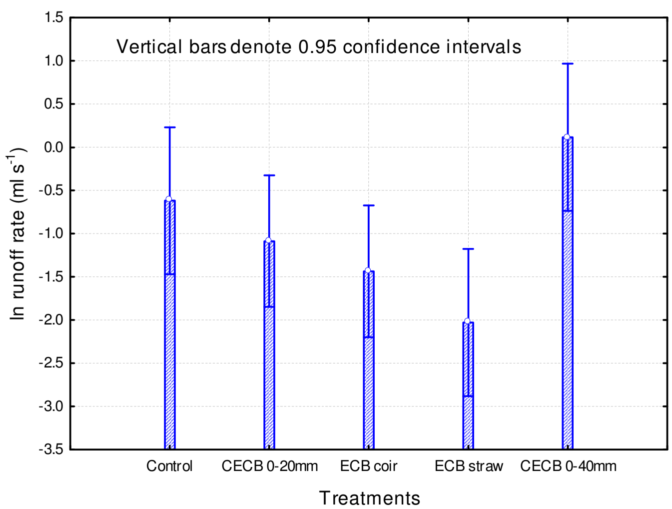


Figure 4.17 Clay loam soil: Effect of treatments on runoff rate (mg l^{-1}) (ln 10 transformed data)

4.4.3 Leachate volume

Results of the Fisher LSD Test ($p < 0.05$) applied to ln transformed values followed a similar trend to runoff volume (ml), with significantly lower leachate volumes (ml) associated with the CECB0-20mm and CECB0-40mm treatments as compared with the ECBs and control since they have a high WSC. The leachate volume (ml) was in the order Control = ECB_s > CECB0-20mm = CECB0-40mm. The total leachate volume generated from CECBs was approximately 4 times less than the volume generated from ECBs (Figure 4.18).

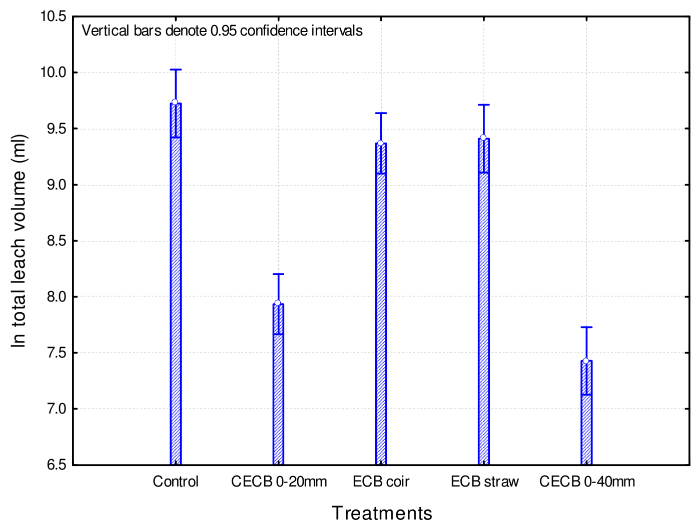


Figure 4.18 Clay loam soil: ln transformed values for leachate total volume (ml) for all treatments

4.4.4 Total Suspended Solid (TSS) concentration and total loss per plot

Following the Fisher LSD Test ($p < 0.05$), using ln transformed values for total suspended solid (TSS) load per plot (g) and concentration (g l^{-1}), significant differences were found between the treatments (Table 4.4). The TSS total load per plot (Figure 4.18) and concentration (Figure 4.19) from CECBs and control was 2 orders of magnitude bigger than for ECBs.

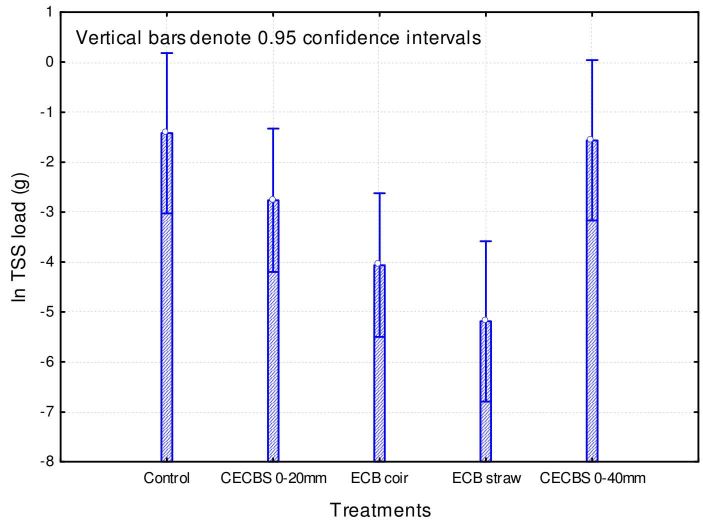


Figure 4.19 Clay loam soil: ln transformed values for TSS total load plot (g) for all treatments

4.4.5 Chemical analysis of runoff and leachate

The Fisher LSD Test ($p < 0.05$) was applied to the runoff and leachate quality indicators listed in Tables 4.8 and 4.9. The weighted means in Tables 4.8 and 4.9 were calculated from the un-transformed data. Homogeneous groups ($p < 0.05$) were generated from data normalized following a mathematical transformation.

Table 4.9 Fisher LSD Test for 5 years PRSE for the weighted means of the runoff quality indicators, for all treatments tested on clay loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)	P-bound plot (mg)	P-bound conc (mg kg^{-1})
$CECB_{0-20}$	2.18 a	0.17 a	106 b	7.20 a	1.91 a	0.14 a	6.07 ab	112 ab
$CECB_{0-40}$	0.91 a	0.36 a	91.6 b	15.8 a	2.07 a	0.47 a	255 a	277 b
ECB_{straw} *	-	-	-	-	-	-	-	-
ECB_{coir}	0.22 ab	0.05 a	2.51 a	1.03 b	2.46 a	0.85 a	1.44 bc	71.2 ab
Control	0.04 b	0.02 a	27.2c	9.11 ab	0.25 b	0.16 a	3.42 a	37.3 a

*Means followed by different letters are significantly different ($p < 0.05$)

*No analysis was done on ECB_{straw} due to excessive missing data

Table 4.10 Fisher LSD Test for 5 years PRSE for the weighted means of the leachate quality indicators, for all treatments tested on clay loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)
$CECB_{0-20}$	0.26 a	0.7 bc	128 a	361 ab	0.14 a	0.30 a
$CECB_{0-40}$	0.1 a	0.14 c	98.7 a	138 b	0.25 a	0.31 a
ECB_{straw}	0.17 a	2.18 ab	99 a	1297 a	0.21 a	2.66 ab
ECB_{coir}	0.25 a	1.12 a	51.5 a	628 ab	0.28 a	3.42 ab
Control	0.22 a	4.26 a	63.3 a	1033 a	0.31 a	6.58 b

*Means followed by different letters are significantly different ($p < 0.05$)

4.4.6 Runoff ammonium-N concentration and total mass of ammonium-N loss from plot

The Fisher LSD Test ($p <0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and ammonium-N loss from the plot (mg), indicated that the control generated lower ammonium-N concentrations as compared with the other treatments. Extremely low values, often below detection limits of auto analyser, were detected for all the treatments (Table 4.10). No significant difference was found between the treatments in relation to the total ammonium-N lost from the plot. No ammonium-N contamination hazard will be generated from CECBs, since the concentration values (mg) were comparable to the control.

4.4.7 Runoff Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

Significant differences were found between the treatments in relation to the Box Cox transformed values total loss of TON per plot (mg) and concentration (mg l^{-1}), following Fisher LSD Test ($p <0.05$). Among the treatments, CECBs generated the highest TON concentration (mg l^{-1}) and total loss of TON per plot (mg) (Table 4.8). The concentrations of Nitrate-N in the $CECB_{0-20}$ and $CECB_{0-40}$ were significantly different (Table 3.3), with mean (n=6) values of 306 and 83.0 mg kg^{-1} respectively. However, no significant difference occurred between the CECBs. Both treatments exceeded ($CECB_{0-20}$ 106 mg l^{-1} and $CECB_{0-40}$ 91.6

mg l^{-1}) the limit of 50 mg l^{-1} to consider fresh water unpolluted according to the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008).

4.4.8 Runoff orthophosphate-P concentration and total loss of orthophosphate-P per plot

The Fisher LSD Test ($p < 0.05$), performed on Box Cox transformed data, indicated that even though the orthophosphate-P concentration (mg l^{-1}) from the control treatments was significantly lower than the other treatments (Figure 4.20), no difference was found in relation to the total orthophosphate-P loss for plot (mg) (Table 4.8). For all treatments the orthophosphate-P concentration (mg l^{-1}) on runoff was below the limits admitted for the UK water quality standard (Tables 2.5 and 2.6).

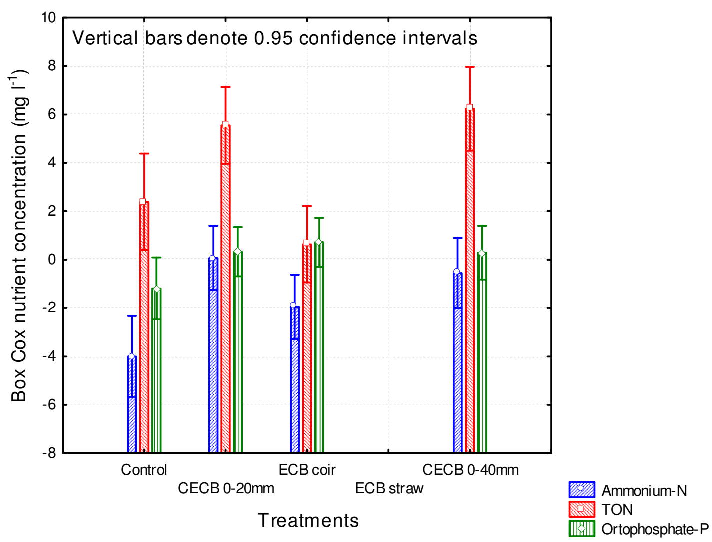


Figure 4.20 Clay loam soil: Concentration (mg l^{-1}) of ammonium-N TON and orthophosphate-P per plot (mg) in runoff (Box Cox transformed values)
* Due to missing data no statistical analysis was applied to ECB_{straw} treatment

4.4.9 Total Sediment bound phosphorous (T-SBP) concentration and total loss of SBP per plot

The Fisher LSD Test ($p < 0.05$) was applied to the Box Cox transformed values for the total loss of SBP per plot (mg), and SQRT transformed values for the

SBP concentration (mg kg^{-1}). The results indicated that SBP concentration (mg l^{-1}) was significantly higher from the $CECB_s$ as compared with all the other treatments (1 order of magnitude) (Table 4.8).

With regards to total loss of SBP per plot (mg $plot^{-1}$), significant differences were observed only between the control with a value of 37.3 mg kg^{-1} and the $CECB0_{0\text{-}40mm}$ value of 227 3 mg kg^{-1} (Table 4.8).

4.4.10 Leachate ammonium-N concentration and total mass of ammonium-N lost from plot

The Fisher LSD Test ($p < 0.05$), using Box Cox transformed values of ammonium-N concentration (mg l^{-1}) indicated that there is no significant difference between the treatments. Due to the reduced leachate volume generate from CECBs, total ammonium-N loss from the plot (mg) from CECBs was significantly lower than all the other treatments (Table 4.9). Furthermore extremely low values often below detection limits of auto analyser for all the treatments were detected.

4.4.11 Leachate Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

No significant differences were found between the treatments in relation to the Box Cox transformed values for TON concentration (mg l^{-1}) following Fisher LSD Test ($p < 0.05$) (Table 4.9). The trend is for higher concentrations of TON (mg l^{-1}) from CECBs treatments although this trend is not significant. Nevertheless due to the reduced volume of leachate, generated from CECBs as compared with the other treatments the total loss of TON per plot were significantly lower (1 order of magnitude) for the CECBs. It is important to note that the TON concentration for all the treatments exceeded the limit permitted (50 mg l^{-1}) by the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008).

4.4.12 Leachate orthophosphate-P concentration and total loss of orthophosphate-P per plot

Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicates that the concentrations (mg l^{-1}) of orthophosphate-P were not significantly different between treatments (Figure 4.21). Since CECBs generate less leachate volume (ml), than all the other treatments, the total loss of orthophosphate-P was significantly lower for CECBs. Table 4.9 shows that the extremely low orthophosphate-P values for all treatments ranged from 0.14 to 0.31 mg l^{-1}. Therefore, for all treatments, the orthophosphate-P concentration in leachate was below the limits set for the UK water quality standard for river (Tables 2.5 and 2.6).

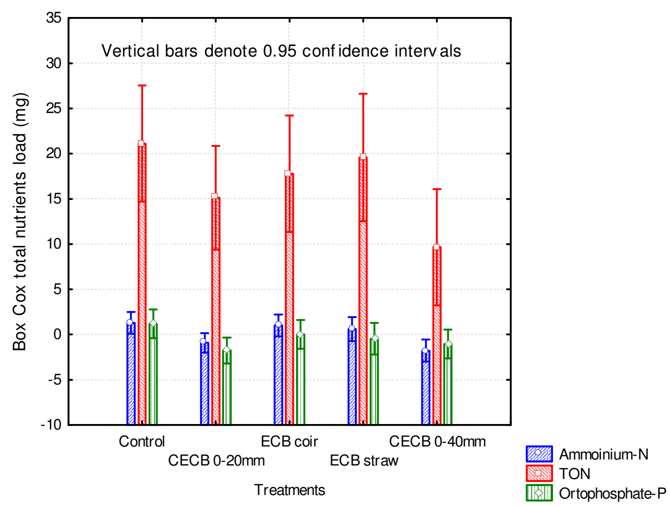


Figure 4.21 Clay loam soil: Total loss of ammonium-N TON and orthophosphate-P concentration (mg l^{-1}) in leachate (Box Cox transformed values)

4.5 Preliminary analysis of the 75 years return period storm event (PRSE)

Results of the Factorial ANOVA analysis indicate significant differences in the dependent variables evaluated as a function of soil and treatment factors. The slope angles 2:1 and 3:1 (horizontal:vertical) factor demonstrated no significant effect on the variables tested.

Table 4.11 Factorial ANOVA analysis, LSD Test ($p < 0.05$) of the dependent variables in relation to slope, soil and treatment factors for the 75 year PRSE

Dependent Variables	Factors		
	Slope	Soil	Treat-ment
Time to runoff initiation (min)	No	Yes	Yes
Total runoff volume (ml)	No	Yes	Yes
Mean runoff rate (ml s^{-1})	No	Yes	No
Total leach volume (ml)	No	Yes	Yes
Total suspended solids (TSS) plot (g $plot^{-1}$)	No	Yes	Yes
Total suspended solids (TSS) concentration (g l^{-1})	No	Yes	Yes
Runoff Total Oxides of Nitrogen (TON) concentration (mg l^{-1})	No	Yes	Yes
Runoff total loss of TON per plot (mg $plot^{-1}$)	No	Yes	No
Runoff ammonium-N concentration (NH_4^+) (mg l^{-1})	No	Yes	Yes
Runoff ammonium-N plot (NH_4^+) (mg $plot^{-1}$)	No	Yes	Yes
Runoff orthophosphate-P concentration (mg l^{-1})	No	Yes	Yes
Runoff orthophosphate-P per plot (mg $plot^{-1}$)	No	Yes	Yes
Sediment bound phosphorous (SBP) concentration (mg kg^{-1})	No	Yes	Yes
Sediment bound phosphorous (SBP) per plot (mg $plot^{-1}$)	No	Yes	No
Leachate Total Oxides of Nitrogen (TON) concentration (mg l^{-1})	No	Yes	Yes
Leachate total loss of TON per plot (mg $plot^{-1}$)	No	Yes	Yes
Leachate ammonium-N (NH_4^+) concentration (mg l^{-1})	No	No	No
Leachate ammonium-N (NH_4^+) plot (mg $plot^{-1}$)	No	No	No
Leachate orthophosphate-P concentration (mg l^{-1})	No	Yes	Yes
Leachate orthophosphate-P per plot (mg $plot^{-1}$)	No	Yes	Yes

The soil slope did not affect the performance of any treatment, thus slope factor is not taken into account in the following analysis.

Because the 75 years PRSE is the continuation of the 5 years PRSE, for the same soil, values for runoff time initiation are equal for both events. For that reason on the 75 years PRSE results section, runoff time initiation variable will be omitted.

4.6 Treatment performances on silt loam soil

Following factorial ANOVA, the Fisher LSD Test ($p < 0.05$) was applied to the runoff and soil loss performance indicators listed in Table 4.10 in relation to the different treatments applied. The weighted means in Table 4.10 were calculated using un-transformed values. Homogeneous groups ($p < 0.05$) were generated from data normalized using a mathematical transformation of the real data.

Table 4.12 Fisher LSD Test for 75 years PRSE for the weighted means of the runoff and soil loss performance indicators for all treatments tested on silt loam

Treatment	Runoff start time (min)	Runoff volume (ml)	Runoff rate (ml s^{-1})	Leachate volume (ml)	TSS mass (g)	TSS conc (g l^{-1})
$CECB_{0-20}$	9.9 a	2246 b	1.71 b	29875 a	1.2 a	0.54 a
$CECB_{0-40}$	14.3 a	1702 ab	2.32 b	26545 a	0.91 a	0.89 a
ECB_{straw}	3.25 c	362 ab	0.22 a	43508 b	0.03 b	0.09 b
ECB_{coir}	3.9 c	527 ab	0.33 ab	43505 b	0.01 b	0.04 c
Control	6.08 ab	196 a	0.13 a	50435 b	0.34 b	0.64 a

*Means followed by different letters are significantly different ($p < 0.05$)

4.6.1 Runoff volume and rate

The Fisher LSD Test ($p < 0.05$) for runoff volume (ml) and rate (ml s^{-1}), using respectively by SQRT and ln transformed values (Table 4.10), demonstrate that CECBs generate significantly more runoff (ml) than ECBs (5 time less volume) and control (10 time less volume) (Figure 4.22). That is in contrast with the runoff volume (ml) and rate (ml s^{-1}) detected from CECBs during the 5years PRSE. After the CECBs reach its saturation, no more water can be stored, and the runoff starts. It is verisimilar assume that once the compost is saturated the water the water followed preferential pathways and the runoff rate (ml s^{-1}) on CECBs compared to the other treatments.

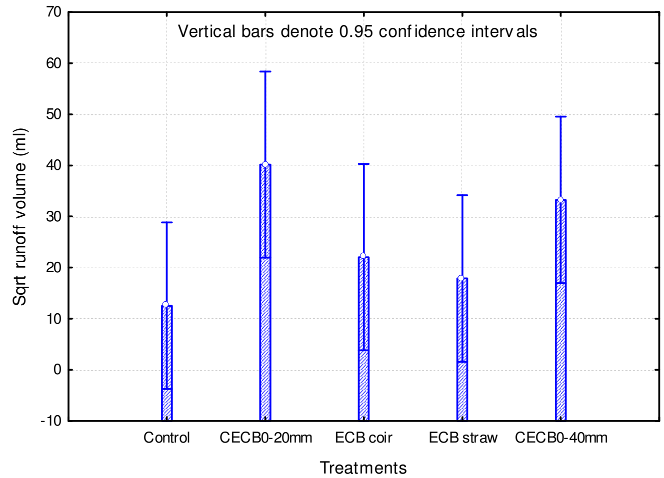


Figure 4.22 Silt loam soil: Effect of treatments on runoff total volume (SQRT transformed data)

4.6.2 Leachate volume

Results of the Fisher LSD Test ($p < 0.05$) applied to ln transformed values demonstrate that, significantly lower (30%) leachate volumes (ml) were associated with the $CECB_s$ treatments as compared with the ECBs and control, due to the compost high WSC. Leachate volume (ml) was in the order Control > ECB_s> $CECB_s$ (Figure 4.23).

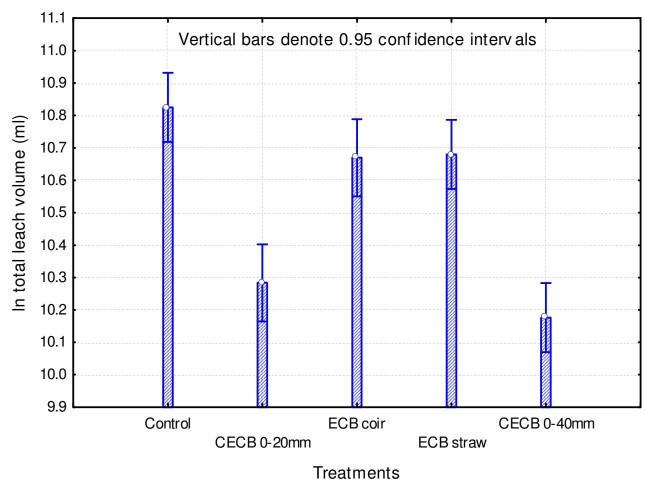


Figure 4.23 Silt loam soil: ln transformed values for leach total volume (ml) for all treatments

4.6.3 Total Suspended Solid (TSS) concentration and total loss per plot

Following the Fisher LSD Test ($p < 0.05$), using ln transformed values for total suspended solid (TSS) load per plot (g) CECBs generate significant more TSS volume (g) than all the other treatments (Figure 4.24) (other treatments being one order of magnitude less) (Table 4.10). TSS concentration (g l^{-1}) was significantly greater on CECBs and control as compared with ECBs (ECBs being one order of magnitude less) (Figure 4.25). Also for the 5 years PRSE the concentration (g l^{-1}) was greater for CECBs, but because their runoff volume (ml) was reduced compared to the other treatments, the total loss of TSS (g) were comparable. High TSS concentration (g l^{-1}) for CECBs can be explained by assuming that most of the TSS is composed by particle detached from the compost rather than from the soil.

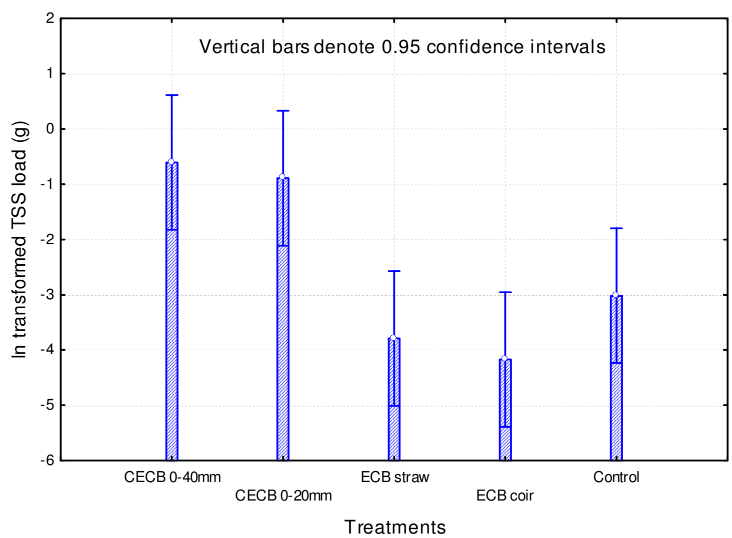


Figure 4.24 Silt loam soil: ln transformed values for TSS total load plot (g) for all treatments

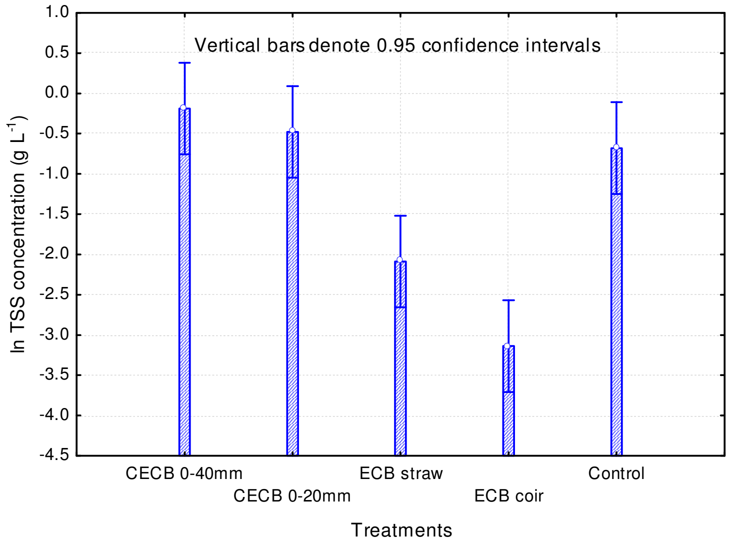


Figure 4.25 Silt loam soil: ln transformed values for TSS concentration (g l⁻for all treatments

4.6.4 Chemical analysis of runoff and leachate

The Fisher LSD Test (p <0.05) was applied to the runoff and leachate quality indicators listed in Table 4.13 and 4.14. The weighted means in Table 4.13 and 4.14 were calculated from the un-transformed data. Homogeneous groups (p <0.05) were generated from data normalized following a mathematical transformation.

Table 4.13 Fisher LSD Test for 75 years PRSE for the weighted means of the runoff quality indicators, for all treatments tested on silt loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)	P-bound plot (mg)	P-bound conc (mg kg^{-1})
$CECB_{0-20}$	0.1 ab	5.99 ab	136 b	507 a	0.1 a	5.43 a	0.1 bc	92.9 a
$CECB_{0-40}$	0.65 b	1.50 a	197 b	314 a	1.15 a	1.65 a	0.08 c	158 a
ECB_{straw}	0.2 b	0.12 ab	0.6 a	0.21 b	0.4 a	0.04 a	0 ab	242 a
ECB_{coir}	0 ab	0.09 ab	3.4 a	2.01 b	0.1 b	0.37 a	0 a	423 a
Control	0.1 a	0 c	4.1 c	30 c	0.2 a	0.06 a	0 a	133 a

* Means followed by different letters are significantly different (p < 0.05)

Table 4.14 Fisher LSD Test for 75 years PRSE for the weighted means of the leachate quality indicators, for all treatments tested on silt loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)
$CECB_{0-20}$	0.29 a	8.31 a	116 c	3543 a	0.27 ab	6.97 a
$CECB_{0-40}$	1.22 a	34.4 a	108 bc	3044 ab	0.24 a	6.7 a
ECB_{straw}	0.13 a	6.49 a	71.3 ab	3108 ab	0.04 ab	1.25 a
ECB_{coir}	0.15 a	5.84 a	87 ab	3699 ab	0.1 ab	4.20 a
Control	0.05 a	2.06 a	36.3 a	1854 b	0.04 b	2.21 a

* Means followed by different letters are significantly different ($p < 0.05$)

4.6.5 Runoff ammonium-N concentration and total mass of ammonium-N lost from plot

The Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) indicated significantly higher (1 order of magnitude) values on CECBs than the other treatments. However, for all the treatments extremely low values often below detection limits of auto analyser were detected (Table 4.11). Due to the higher ammonium-N concentration (mg l^{-1}) and runoff volume (ml) for CECBs, the total ammonium-N (mg) load values was significantly higher as compared to the other treatments. However total of ammonium-N load values for all the treatments were extremely low (ranging from 0 -5.99 mg) (Table 4.11).

4.6.6 Runoff Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

Significant differences were found between the treatments in relation to the Box Cox transformed values of total loss of TON per plot (mg) and TON concentration (mg l^{-1}) following Fisher LSD Test ($p < 0.05$). TON concentration (mg l^{-1}) was significantly higher for CECBs (Table 4.13).

The concentrations of Nitrate-N in the $CECB_{0-20}$ and $CECB_{0-40}$ were significantly different (Table 3) with mean (n=6) values of 306 and 83.0 mg kg^{-1}, respectively. However, no significant difference occurred between CECBs. TON concentration in runoff from CECBs was 3 times in excess of the

23concentration allowed, according to the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008) (50 mg l^{-1}). This implies that in Nitrate Vulnerable Zones, the use of CECBs might be restricted unless the source of compost used can be carefully monitored to ensure low levels of nitrate.

4.6.7 Runoff orthophosphate-P concentration and total loss of orthophosphate-P per plot

Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicated significant differences between the treatments in relation to the orthophosphate-P concentration (mg l^{-1}) (Table 4.14). The ECB_{coir} treatment demonstrated the lowest value. However for all treatments the orthophosphate-P concentration in runoff was below the limits associated with the UK water quality standard (Tables 2.5 and 2.6).
No significant difference in relation to the total loss of orthophosphate-P per plot (mg) was found, between the treatments.

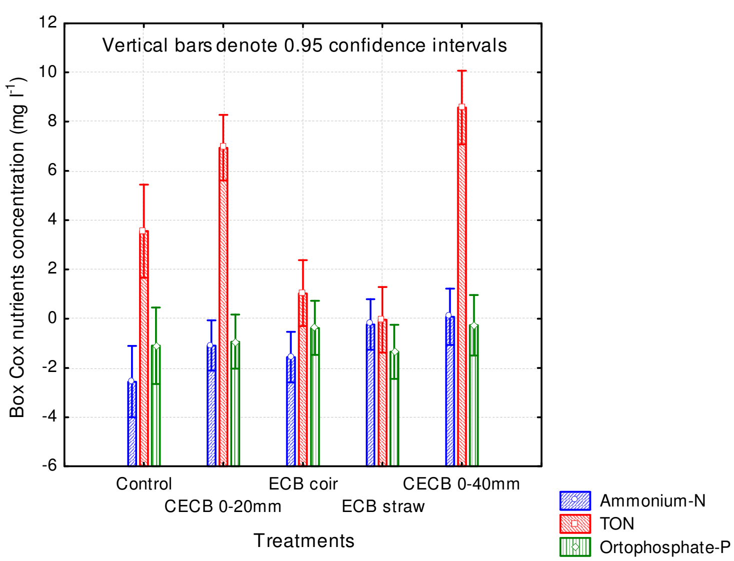


Figure 4.26 Silt loam soil: Total loss of ammonium-N, TON and orthophosphate-P per plot (mg) in runoff (Box Cox transformed values)

4.6.8 Total Sediment bound phosphorous (T-SBP) concentration and total loss of SBP per plot

The Fisher LSD Test ($p < 0.05$) was applied to the Box Cox transformed values for the total loss of SBP per plot (mg), and SQRT transformed values for the SBP concentration (mg kg^{-1}). Even though the CECBs SBP concentration was lower as compared to the other treatments, the difference was not significant (Figure 4.28). The results indicate that SBP total load (mg) was significantly higher from the CECBs due to the highest runoff volume compared to the other treatments. This is in direct contrast to the 5-year PRSE.

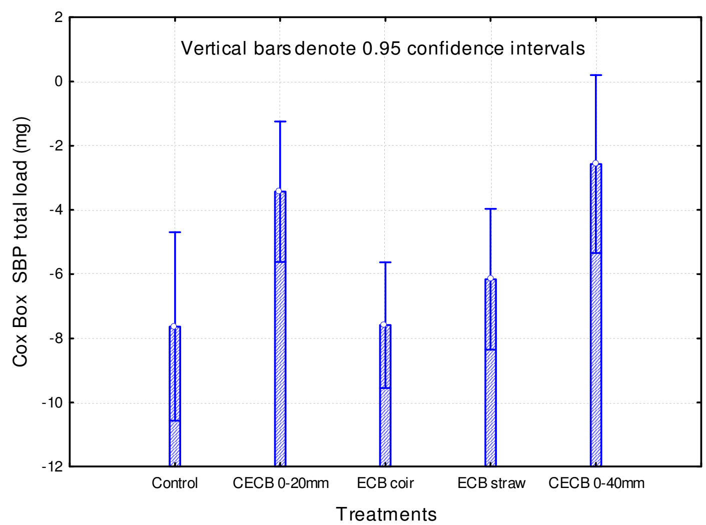


Figure 4.27 Silt loam soil: Effect of treatment on SBP concentration (mg kg^{-1}) in runoff (SQRT transformed values)

4.6.9 Leachate ammonium-N concentration and total mass of ammonium-N lost from plot

The Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and ammonium-N lost from the plot (mg) indicated that there is no significant difference between the treatments (Figure 4.29). Furthermore, for all the treatments extremely low values often below the detection limits of auto analyser were detected (Table 4.12).

4.6.10 Leachate Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

Significant differences were found between the treatments in relation to the Box Cox transformed values for TON concentration (mg l^{-1}) following Fisher LSD Test ($p < 0.05$). Total losses of TON per plot (mg) were significantly higher from CECBs as compared to the other treatments. However because CECBs generated less leachate than the other treatments, total losses of TON per plot (mg) were comparable to the ECBs total loss of TON (Table 4.12). TON leachate concentration (mg l^{-1}) for the 75 years PRSE from all the treatments was not dissimilar than from the 5 years PRSE. Total loss of TON (mg), during the 5 years PRSE were significantly lower than during the 75 years PRSE, because the leachate volume (ml) was reduced.

4.6.11 Leachate orthophosphate-P concentration and total loss of orthophosphate-P per plot

Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicated that the concentration of orthophosphate-P were significantly higher for CECBs as compared to the other treatments. However because CECBs generated less leachate volume (ml), than all the other treatments, the total loss of orthophosphate-P was comparable (Figure 4.29). Table 4.12 shows the extremely low with mean values for all treatments which, ranged from 0.04 to 0.27 mg l^{-1}. Consequently, for all treatments the orthophosphate-P concentration in leachate was below the limits acceptable for the UK water quality standard for rivers (Tables 2.5 and 2.6).

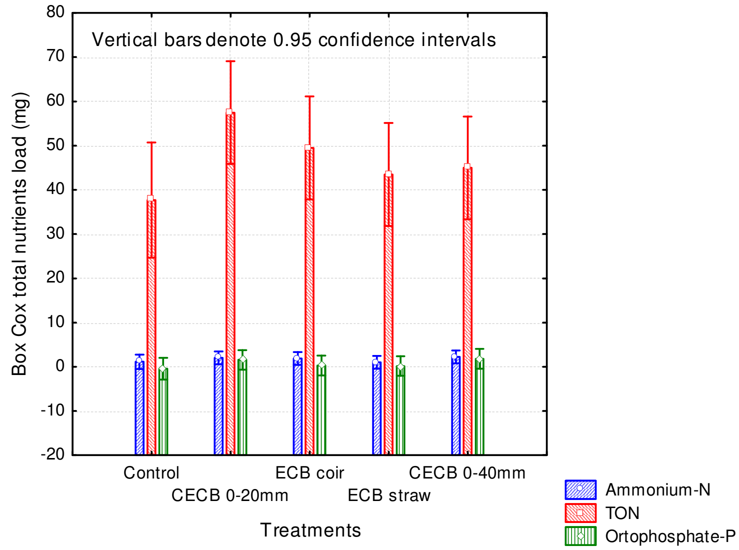


Figure 4.28 Silt loam soil: Total loss of ammonium-N, TON and orthophosphate-P per plot (mg) in runoff (Box Cox transformed values)

4.7 Treatment performances on sandy loam soil

Following factorial ANOVA, the Fisher LSD Test ($p < 0.05$) was applied to the runoff and soil loss performance indicators listed in Table 4.13 in relation to the different treatments applied. The weighted means in Table 4.13 were calculated using un-transformed values. Homogeneous groups ($p < 0.05$) were generated from data normalized using a mathematical transformation of the real data.

Table 4.15 Fisher LSD Test for 75 years PRSE for the weighted means of the runoff and soil loss performance indicators for all treatments tested on sandy loam soil

Treatment	Runoff start time (min)	Runoff volume (ml)	Runoff rate (ml s^{-1})	Leachate volume (ml)	TSS mass (g)	TSS conc (g l^{-1})
$CECB_{0-20}$	18.3 a	461 a	0.67 a	27352 a	0.18 a	0.15 a
$CECB_{0-40}$	18.6 a	74 a	0.07 a	26651 a	0.05 a	0.43 a
ECB_{straw}	3.42 b	423 a	0.26 a	39319 b	0.01 a	0.04 a
ECB_{coir}	3.22 b	526 a	0.33 a	41100 bc	0.03 a	0.09 a
Control	5.45 b	517 a	0.34 a	47330 c	0.39 a	0.47 a

* Means followed by different letters are significantly different ($p < 0.05$)

4.7.1 Runoff volume and rate

The Fisher LSD Test ($p < 0.05$) for runoff volume (ml) and rate (ml s^{-1}), using SQRT and ln transformed values respectively (Table 27), indicate no significant differences between the treatments due to the high variations observed.

4.7.2 Leachate volume

Results of the Fisher LSD Test ($p < 0.05$) applied to ln transformed values demonstrate that lower leachate volumes (ml) were associated with the $CECB_s$ treatments as compared with the ECBs and control. Leachate volume (ml) was in the order Control > ECB_s> $CECB_s$. This trend is similar to that observed for the 5 year PRSE.

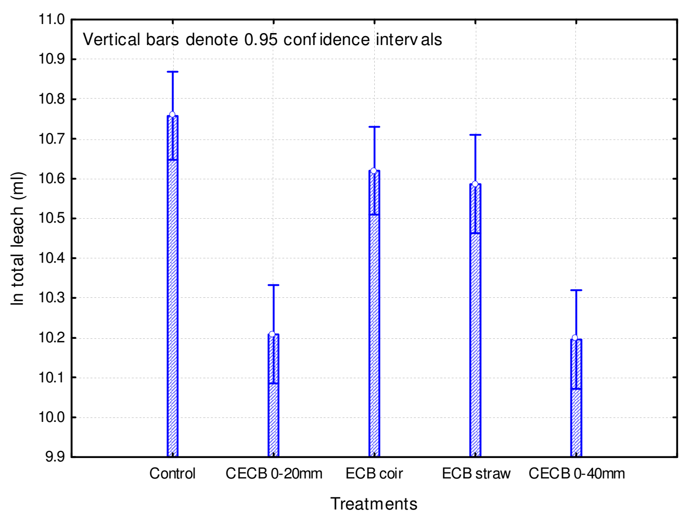


Figure 4.29 Sandy loam soil: ln transformed values for leach total volume (ml) for all treatments

4.7.3 Total Suspended Solid (TSS) concentration and total loss per plot

Following the Fisher LSD Test ($p < 0.05$), using ln transformed values for total suspended solid (TSS) load per plot (g) and concentration (mg l^{-1})no significant difference was found between the treatments. On the sandy loam soil, the values of TSS or all the treatments were extremely low compared to the other soil types tested (Table 4.13).

4.7.4 Chemical analysis of runoff and leachate

The Fisher LSD Test ($p < 0.05$) was applied to the runoff and leachate quality indicators listed in Table 4.14 and 4.15. The weighted means in Table 4.14 and 4.15 were calculated from the un-transformed data. Homogeneous groups ($p < 0.05$) were generated from data normalized following a mathematical transformation.

Table 4.16 Fisher LSD Test for 75 years PRSE for the weighted means of the runoff quality indicators, for all treatments tested on sandy loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)	P-bound plot (mg)	P-bound conc (mg kg^{-1})
$CECB_{0-20}$	0.81 a	1.5 a	76.2 a	53.4 a	0.8 a	0.48 a	0 a	92.5 a
$CECB_{0-40}$	1.1 a	0.37 a	163 a	106 a	1.12 a	1.35 a	0a	187.2 a
ECB_{straw}	0.13 a	0.54 a	6.7 a	58.5 a	0.81 a	0.51 a	0a	221 a
ECB_{coir}	0.08 a	0.24 a	63.1 a	22.3 a	1.03 a	0.32 a	0a	232 a
Control	0.06 a	0.12 a	49 a	11.6 a	0.61 a	0.39 a	0a	37.3 a

* Means followed by different letters are significantly different ($p < 0.05$)

Table 4.17 Fisher LSD Test for 5 years PRSE for the weighted means of the leachate quality indicators, for all treatments tested on sandy loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)
$CECB_{0-20}$	0.17 a	5.17 a	211 a	6103 a	0.32 a	5.21 a
$CECB_{0-40}$	0.26 a	6.47 a	251 a	6319a	0.19 a	8 a
ECB_{straw}	0.13 a	5.24 a	164 a	6354 a	0.06 a	2.22 a
ECB_{coir}	0.26 a	10.86 a	174 a	7268 a	0.13 a	5.13 a
Control	0.16 a	7.85 a	165 a	8182 a	0.16 a	7.9 a

* Means followed by different letters are significantly different ($p < 0.05$)

4.7.5 Runoff ammonium-N concentration and total mass of ammonium-N lost from plot

The Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and total of ammonium-N load (mg $plot^{-1}$) indicate that there is no significant difference between treatments (Table 4.14). Further, for all the treatments extremely low values were detected.

4.7.6 Runoff Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

No significant differences were found between the treatments in relation to the Box Cox transformed values of TON concentration (mg l^{-1}) and total loss of TON per plot (mg) following Fisher LSD Test ($p < 0.05$).However, the trend is for higher concentrations of TON (mg l^{-1}) from CECBs treatments although this trend is not significant (Table 4.14). For CECBs, TON concentrations (mg l^{-1}) exceeded the concentration value allowed, according to the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008) (50 mg l^{-1}). The TON concentration for $CECB_{0\text{-}20}$ and $CECB_{0\text{-}40}$ were 76.2 and 163 (mgl^{-1}) respectively.

4.7.8 Runoff orthophosphate-P concentration and total loss of orthophosphate-P per plot

Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicate no significant difference between the treatments in relation to the orthophosphate-P concentration (mg l^{-1}) and total load (mg) (Table 4.14). However, for all treatments the orthophosphate-P concentration on runoff was below the limits established by UK water quality standard (Tables 2.5 and 2.6).

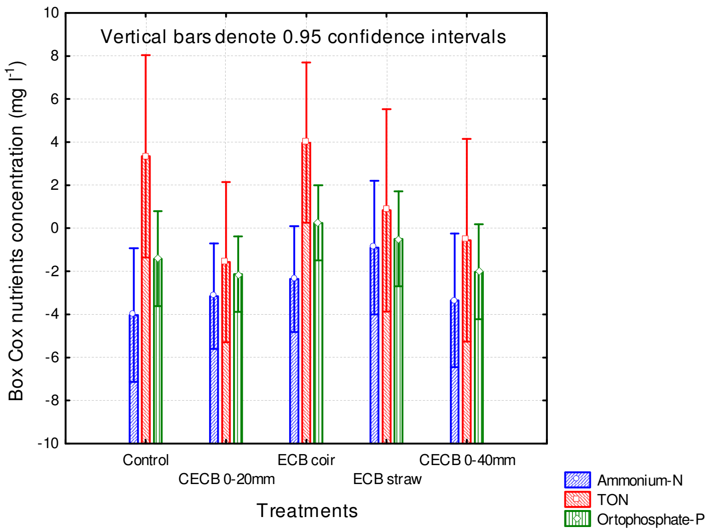


Figure 4.30 Sandy loam soil: Concentration (mg l^{-1}) of ammonium-N, TON and orthophosphate-P per plot in runoff (Box Cox transformed values)

4.7.9 Total Sediment bound phosphorous (SBP) concentration and total loss of SBP per plot

Even though the trend was for higher SBP concentrations for the ECBs, the difference was no significant. Due to the low amounts of TSS lost (mg) for all the treatments the SBP per plot was often below the detection limit (Table 4.15).

4.7.10 Leachate ammonium-N concentration and total mass of ammonium-N lost from plot

In similarity with the 5-year PRSE and with the other test soils, no significant difference in ammonium-N concentration (mg l^{-1}) and ammonium-N lost from the plot (mg) was observed between treatments (Table 4.15).

4.7.11 Leachate Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

In similarity with the 5-year PRSE and with the other test soils, no significant differences were found between the treatments in relation to the Box Cox transformed values for TON concentration (mg l^{-1}) and total losses of TON per plot (mg) (Table 4.15).

Further, the TON concentration (mg l^{-1}) values for all the treatments exceeded (3 times higher) the acceptable nitrate concentration set by the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008) (50 mg l^{-1}). The TON concentration for all treatments ranged from 165 and 211 (mgl^{-1}).

4.7.12 Leachate orthophosphate-P concentration and total loss of orthophosphate-P per plot

Again, in similarity with the 5-year PRSE and with the other test soils the concentration (mg l^{-1}) and total load (mg) of orthophosphate-P per plot were not significantly different between the treatments. Table 4.16 shows the extremely low values for all treatments ranging from 0.06 to 0.32 mg l^{-1}. Consequently, for all treatments the orthophosphate-P concentration (mg l^{-1}) in runoff was well within acceptable levels.

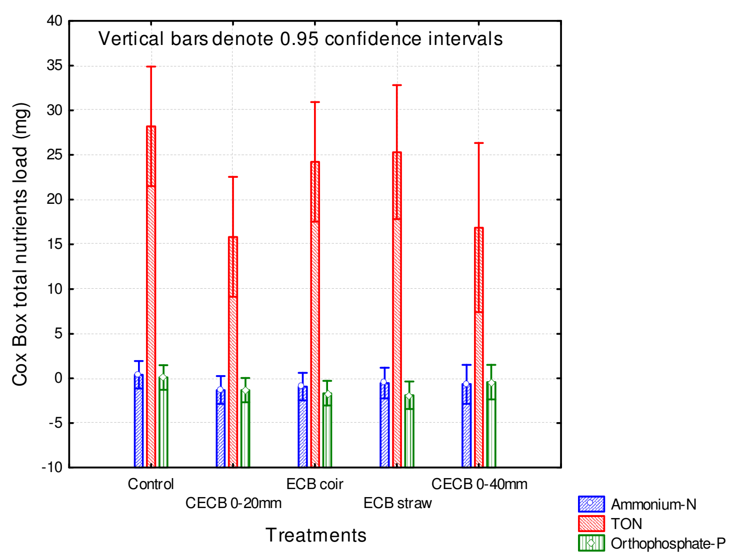


Figure 4.31 Sandy loam soil: Total loss of ammonium-N, TON and orthophosphate-P per concentration (mg l^{-1}) in leachate (Box Cox transformed values)

4.8 Treatment performances on clay loam soil

Following factorial ANOVA, the Fisher LSD Test ($p < 0.05$) was applied to the runoff and soil loss performance indicators listed in Table 4.16 in relation to the different treatments applied. The weighted means in Table 4.16 were calculated using un-transformed values. Homogeneous groups ($p < 0.05$) were generated from data normalized using a mathematical transformation of the real data.

Table 4.16 Fisher LSD Test for 75 years PRSE for the weighted means of the runoff and soil loss performance indicators for all treatments tested on clay loam soil

Treatment	Runoff start time (min)	Runoff volume (ml)	Runoff rate (ml s^{-1})	Leachate volume (ml)	TSS mass (g)	TSS conc (g l^{-1})
$CECB_{0-20}$	11 c	1610 ab	1.36 ac	28056 c	1.32 b	0.87 a
$CECB_{0-40}$	12.2 c	5688 b	5.12 a	22448 b	4.21 bc	1.29 a
ECB_{straw}	4.1 ab	185 a	0.12 b	42624 a	0.01 a	0.09 b
ECB_{coir}	3.29 a	565 a	0.35 bc	42114 a	0.16 a	0.18 b
Control	4.48 b	4299 b	2.77 a	44706 a	27.1 c	2.34 a

* Means followed by different letters are significantly different ($p < 0.05$)

4.8.1 Runoff volume and rate

The Fisher LSD Test ($p < 0.05$) for runoff volume (ml) and rate (ml s^{-1}), using respectively by SQRT and ln transformed values (Table 4.16), demonstrate that CECBs generate significantly more runoff total volume (ml) and rates (ml s^{-1}) (1 order of magnitude) as compared with the ECBs and control (Figure 4.32 and 4.33). This is in direct contrast to the 5-year PRSE. This has major implications for the use of CECBs for storm water management under extreme rainfall events.

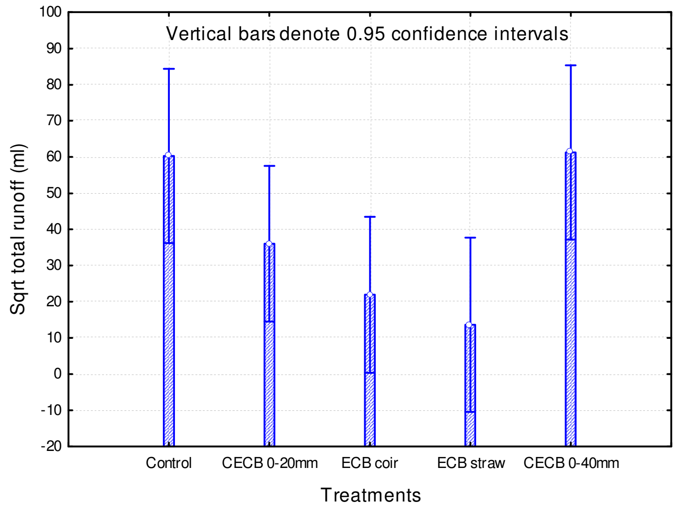


Figure 4.32 Clay loam soil: Effect of treatments on runoff total volume (ml) (SQRT transformed data)

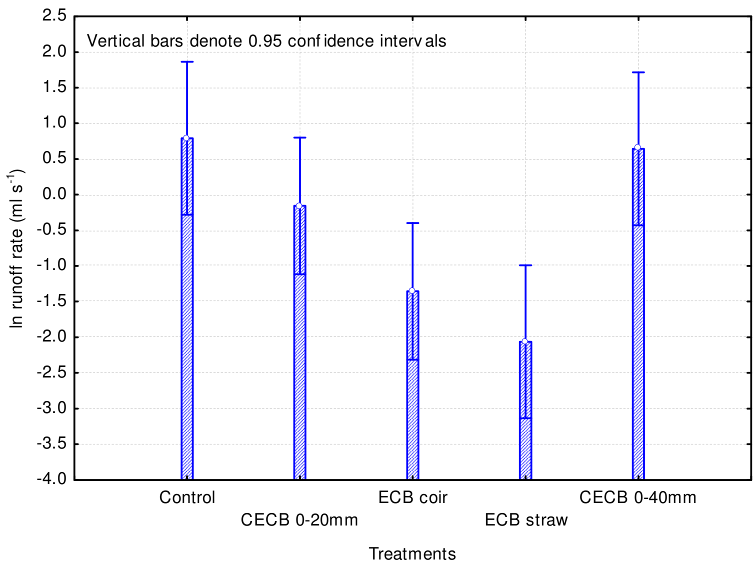


Figure 4.33 Clay loam soil: Effect of treatments on runoff rate (ml s^{-1}) (ln transformed data)

4.8.2 Leachate volume

In similarity with the 5-year PRSE and with the other test soils, lower leachate volumes (ml) were associated with the $CECB_s$ treatments as compared with the ECBs and control. Leachate volume was in the order Control > ECB_s> $CECB_s$ (Figure 4.34).

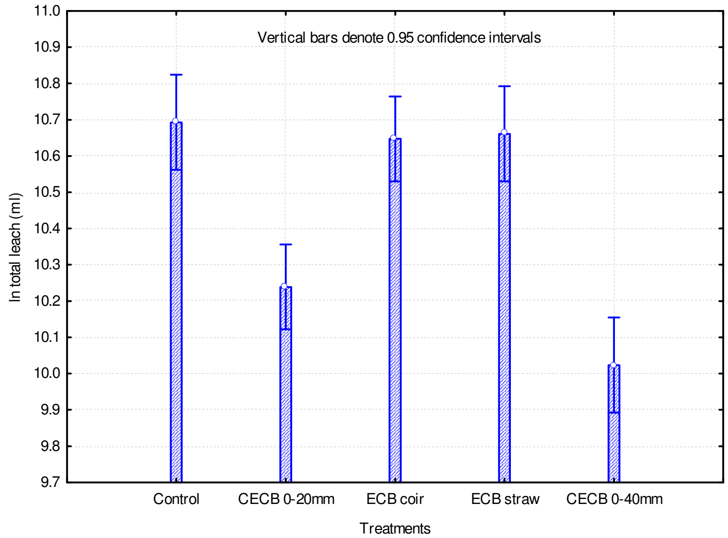


Figure 4.34 Clay loam soil: ln transformed values for leach total volume (ml) for all treatments

4.8.3 Total Suspended Solid (TSS) concentration and total loss per plot

In similarity with the 5-year PRSE and with the other test soils CECBs and the control generate significantly higher TSS loads per plot (g) and concentrations (g l^{-1}) as compared with the ECB treatments (Table 4.16 and Figure 4.35).

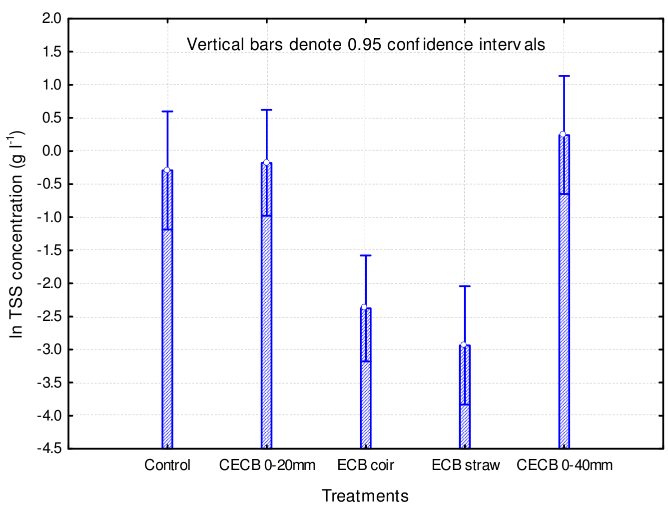


Figure 4.35 ln transformed values for TSS concentration (g l^{-1}), for all treatments tested on clay loam soil

4.8.4 Chemical analysis of runoff and leachate

The Fisher LSD Test ($p < 0.05$) was applied to the runoff and leachate quality indicators listed in Table 4.17 and 4.18. The weighted means in Table 4.17 and 4.18 were calculated from the un-transformed data. Homogeneous groups ($p < 0.05$) were generated from data normalized following a mathematical transformation.

Table 4.17 Fisher LSD Test for 75 years PRSE for the weighted means of the runoff quality indicators, for all treatments tested on clay loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)	P-bound plot (mg)	P-bound conc (mg kg^{-1})
$CECB_{0\text{-}20}$	2.06 a	2.77 a	188 b	322 a	2.48 ab	2.92 ab	0.15 a	110 a
$CECB_{0\text{-}40}$	4.17 a	29.8 a	128 b	170 a	2.31 ab	4.46 b	1.87 a	260 a
ECB_{straw}*	-	-	-	-	-	-	-	-
ECB_{coir}	1.52 ab	0.49 a	3.23 ac	1.68 b	6.72 b	1.14 ab	0 a	77 b
Control	0.13 b	0.18 a	26.3 c	88.8 a	0.37 a	1.31 ab	0.3 a	71 a

* Due to missing data no statistical analysis was applied to ECB_{straw} treatment
* Means followed by different letters are significantly different ($p < 0.05$)

Table 4.18 Fisher LSD Test for 75 years PRSE for the weighted means of the leachate quality indicators, for all treatments tested on clay loam soil

Treatment	Amm conc (mg l^{-1})	Amm plot (mg)	TON conc (mg l^{-1})	TON plot (mg)	Ortho-P conc (mg l^{-1})	P-orto plot (mg)
$CECB_{0\text{-}20}$	0.32 a	8.67 a	170 c	4728 a	0.14 a	3.8 a
$CECB_{0\text{-}40}$	0.15 a	3.14 a	108 abc	2331 ab	6.82b	132 b
ECB_{straw}	0.13 a	5.45 a	122 bc	5356 a	0.13 a	5.68 ab
ECB_{coir}	0.23 a	9.96 a	48.7 a	2099 b	0.16 ab	6.59 ab
Control	0.19 a	8.77 a	56.2 ab	2404 ab	0.19 ab	9.2 ab

* Means followed by different letters are significantly different ($p < 0.05$)

4.8.5 Runoff ammonium-N concentration and total mass of ammonium-N lost from plot

In contrast with all the previous results, the Fisher LSD Test ($p < 0.05$), using by Box Cox transformed values of ammonium-N concentration (mg l^{-1}) and total load (mg) indicate orders a magnitude higher values from CECBs as compared with the control treatments. ECB_{coir} demonstrate values intermediate between CECBs and the control. For ECB_{straw}, insufficient data was generated to facilitate statistical analysis (Table 4.17).

4.8.6 Runoff Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

The results indicate that total loss of TON (mg) and concentration (mg l^{-1}) was significantly higher from CECBs as compared to the control and ECB_{coir} treatments (Table 4.17).

However, no significant difference occurred between CECBs. CECBs concentration values were three times in excess of the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008).

4.8.7 Runoff orthophosphate-P concentration and total loss of orthophosphate-P per plot

Fisher LSD Test ($p < 0.05$) performed on Box Cox transformed data indicate significant differences between the treatments in relation to the orthophosphate-P concentration (mg l^{-1}) and total load (mg) (Table 4.17).

Even though the difference was minimal, significantly lower orthophosphate-P concentration (mg l^{-1}) and total load (mg $plot^{-1}$) values were observed from the control treatments. Further for all treatments the orthophosphate-P concentration in runoff was within acceptable levels.

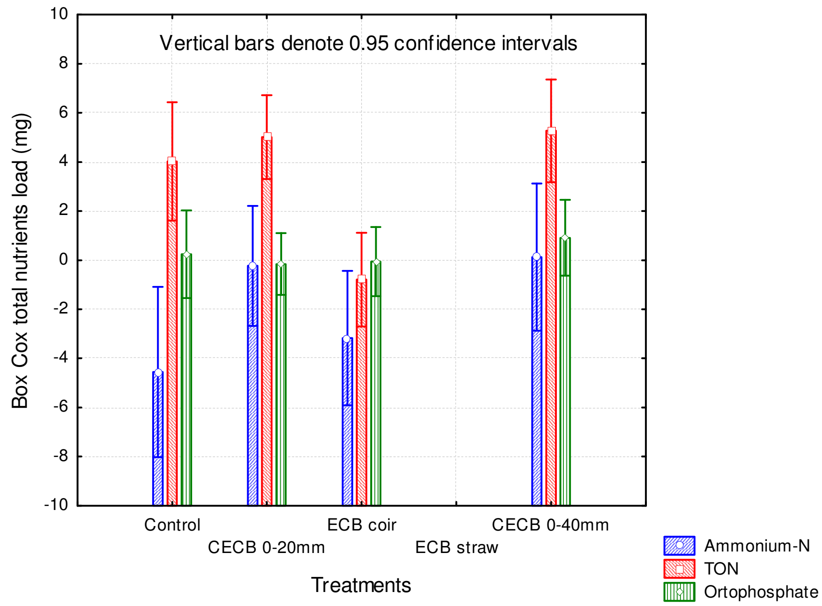


Figure 4.36 Clay loam soil: Total load of ammonium-N, TON and orthophosphate-P per plot (mg) in runoff (Box Cox transformed values)

*Due to missing data no statistical analysis was applied to ECB_{straw} treatment

4.8.8 Total Sediment bound phosphorous (SBP) concentration and total loss of SBP per plot

Even though the CECBs SBP concentration (mg l^{-1}) and total SBP load (mg) were higher as compared to the other treatments, the difference was not significant. The results indicate that SBP total load (mg) from the CECBs was significantly higher as compared to the ECB_s.

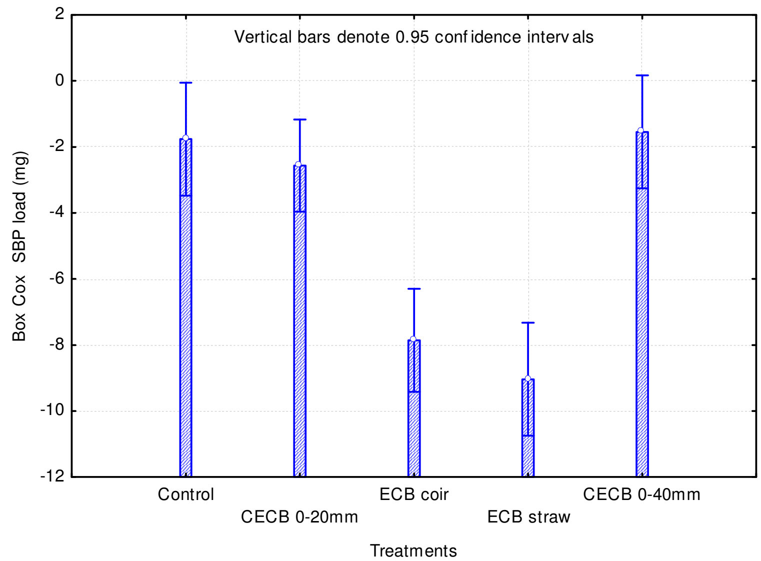


Figure 4.37 Clay loam soil: Effect of treatment on total of SBP loss (mg) in runoff (SQRT transformed values)

4.8.9 Leachate ammonium-N concentration and total mass of ammonium-N lost from plot

In similarity with the 5-year PRSE and with the other test soils, no significant difference in ammonium-N concentration (mg l^{-1}) and ammonium-N lost from the plot (mg) were observed between treatments.

4.8.10 Leachate Total Oxides Nitrogen (TON) concentration and total loss of TON per plot

In similarity with the 5-year PRSE, significant differences were found in TON leachate concentration (mg l^{-1}) and total load (mg), between treatments. Leachate concentration (mg l^{-1}) and total load (mg) were significantly higher for CECBs and ECB_{straw} as compared to the other treatments. However because CECBs generate less leachate than the other treatments, total losses of TON per plot (mg) were comparable to those observed for ECBs.

CECBs and ECB_{straw} TON concentration (mg l^{-1}) exceeded the maximum permissible concentration established under the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008).

4.8.11 Leachate orthophosphate-P concentration and total loss of orthophosphate-P per plot

The results indicate that the concentration and total loss of orthophosphate-P were significantly higher from the CECB0-40mm treatment as compared with the ECBs. However, because CECBs generate less leachate volume (ml), than all the other treatments, the total loss of orthophosphate-P was comparable.

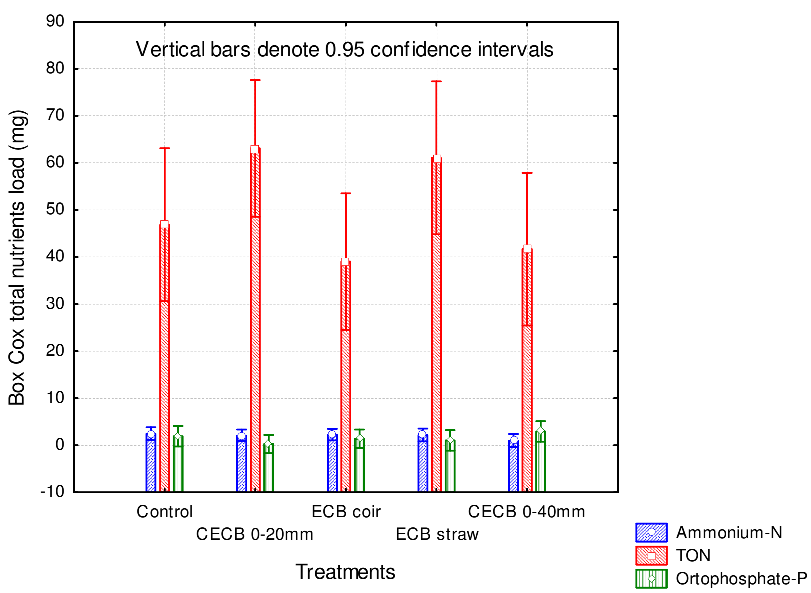


Figure 4.38 Clay loam soil: Total loss of ammonium-N, TON and orthophosphate-P per concentration (mg l^{-1}) in leachate (Box Cox transformed values)

4.9 Resume chapter 4

For all three soil types the runoff from CECBs started significantly later as compared with control. The delay was approximately 4 minutes on silt, 12 minutes on sand and up to 5 minutes on clay.
ECB treatments instead reduced the runoff time compared to the control plot by approximately 1 minute on clay, 2 minutes on sand and 3 minutes on silt.

The results of the Exp_{WB} calculations demonstrated that the CECBs are able to retain a significantly greater percentage of incoming rainfall than the ECB treatments (Figure 4.39). This is also manifested in the significantly lower leachate rates associated with CECBs treatments.

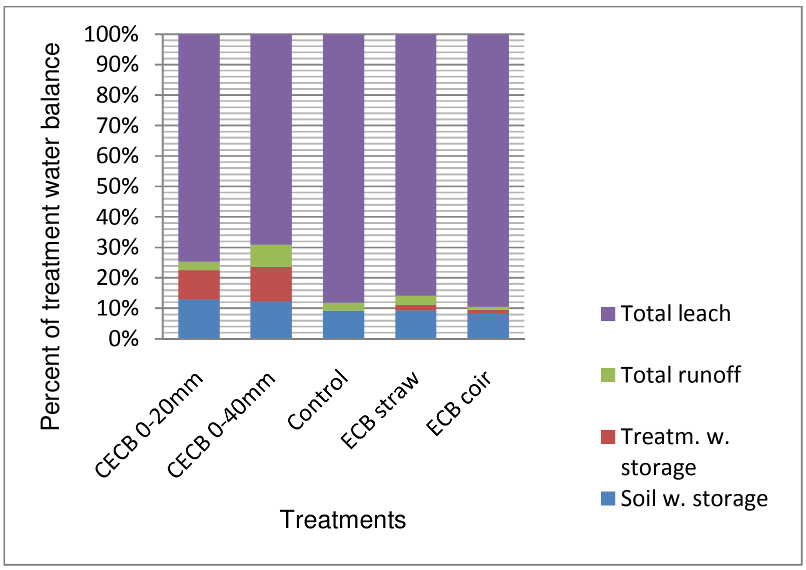


Figure 4.39 Experimental water balance in relation to the treatments tested

The lower water storage (WS) of the ECBs in comparison with the CECBs was not only attributable to the different volumes of material applied but also to the water storage capacity (WSC). Due to differences in product thickness, the ECBs have 5 times less volume than the CECBs. However, even though the comparative difference in WSC was reduced by assuming equal volumes, the WSC of the CECBs was still 16% greater than that of the ECBs.

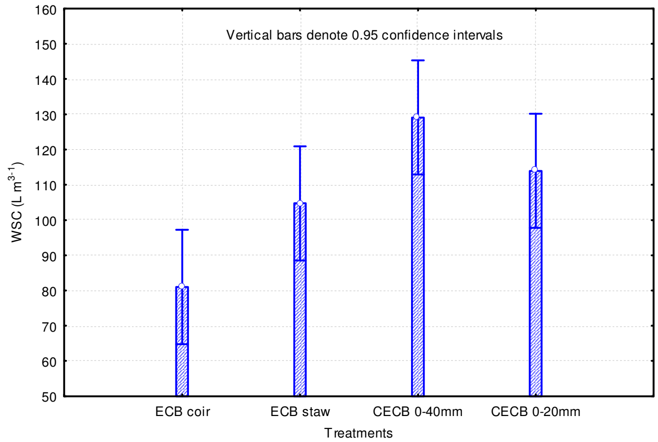


Figure 4.40 Water Storage Capacity WSC (l m^{3-1}) of the treatments

Figure 4.41 illustrates, for brevity only on silt loam soil, how for the first 15 minutes (5-year PRSE) the $CECB_{0\text{-}20mm}$ was able to reduce the runoff volume (ml) by approximately 80% as compared to the control.

For the last 15 minutes (75-year PRSE) the efficiency decline of CECBs in terms of runoff control was more pronounced. The results demonstrated higher runoff rates and cumulative runoff volume with the CECBs than with the ECB and control treatments (Figure 5.5). The same trend was shown also by the other soil types.

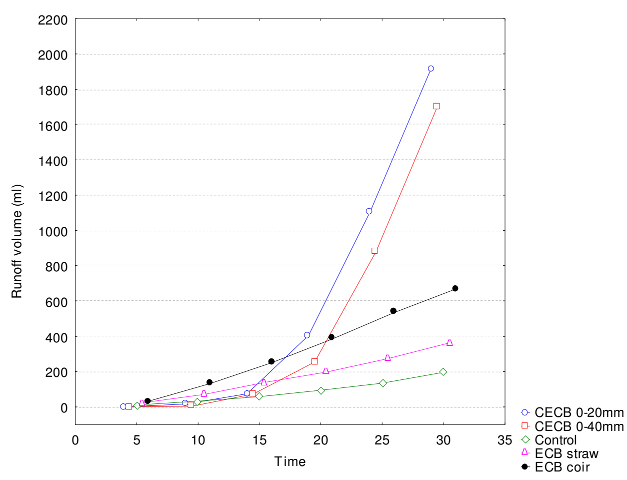


Figure 4.41 75-year PRSE: Cumulative runoff curves (ml), for all treatments, on silt loam soil

Although the runoff volume (ml) for the 5 years PRSE was significantly lower with CECBs as compared to the ECBs and control treatments, due to the higher concentration (g l^{-1}), the TSS loss per plot (g $plot^{-1}$) was comparable for all the treatments.

For the 75-year PRSE the differences in total loss of TSS (g $plot^{-1}$) and TSS concentration (g l^{-1}) between the ECBs, CECBs and control on sandy loam were comparable. On silt the TSS concentration (g l^{-1}) for CECBs was comparable to control but significantly higher than for ECBs (1 order of magnitude). With the CECBs, also the TSS loss per plot (g $plot^{-1}$) was significantly higher than with ECBs (2 orders of magnitude) and the control (3 times). On clay the TSS concentration (g l^{-1}) and TSS loss per plot (g $plot^{-1}$) were higher than ECBs (2 orders of magnitude) and comparable to the control.

In relation to the different PDS of the compost used during the 5-year PRSE test, on silt and sandy loam soil, the runoff volume (ml) and rate (ml s^{-1}) and total loss of TSS (g $plot^{-1}$) from the two CECBs treatments was comparable. In contrast, for the clay loam treatments, runoff volume (ml) and rate (ml s^{-1}) from the $CECB_{0\text{-}40mm}$ was 5 times greater than that observed with $CECB_{0\text{-}20mm}$ treatments.

From the chemical analyses of the runoff and leachate ammonium-N concentrations (mg l-1), no significant differences were observed between the CECBs and the other treatments, irrespective of soil type or PRSE.

No significant differences were observed in runoff and leachate total loss of TON per plot (mg) or TON concentration (mg l^{-1}) between the two CECBs. Instead, compared to the other treatments, the TON per plot (mg $plot^{-1}$) and TON concentration (mg l^{-1}) were significantly higher, often 2 times greater. This trend was comparable across all soil types.

The Orthophosphate-P concentration (mg l^{-1}) and total loss of Orthophosphate-P per plot (mg $plot^{-1}$) in both leachate and runoff were not significantly different between the treatments across all the soil types of PRSE.

With regard to sediment bound phosphorous (SBP), due to the small mass of sediment collected (>0.05 g) and potential instrumental and dilution errors, the results presented in this thesis cannot be considered as conclusive. Further research would be needed to elucidate this aspect of the research.

5. Discussion

From the analysis of the experimental water balance it emerged that CECBs are significantly better than current BMPs in delaying the runoff initiation time. This is in large part due to the significantly higher WSC of the CECBs as compared with the ECBs, as proven by the Exp_{WB}.
This result is in line with the findings of Faucette et al., (2007) and Glanville et al., (2004) who suggest that this was due to the water storage capacity of the CECBs. ECBs instead demonstrated a deficiency in delaying runoff initiation as compared with the CECBs and control treatments.

Furthermore, because runoff was initiated from the ECBs treatments before the control plots, it suggested that the matrix of the ECBs promote runoff. This may in part be due to a certain degree of hydrophobicity, associated with the ECBs tested. Thus water followed preferential pathways within the ECBs matrix rather than moving vertically through the ECB as leachate. However, although the runoff on ECBs started earlier than the control and CECBs treatments, its rate was lower and remained relatively constant. A comparable trend could be seen across all soil types.

CECBs were efficient in controlling runoff by delaying the runoff initiation for the 5-year PRSE. However, this advantage was lost once the CECB achieved saturation. This is particularly true on clay and silt loam, where after compost application the infiltration rate of the soil apparently decreased. Thus, once the compost blanket cannot store any more water, runoff starts at high rate, compared to control.

The horizontal movement of water through the CECBs, once saturation is achieved, is supported by visual inspections at runoff collecting trough. On numerous occasions, flowing water was detected at the CECBs/soil interface, particularly with the $CECB_{0\text{-}40mm}$ treatments (Figure 5.1). For $CECB_{0\text{-}20mm}$

treatments, which contained a significantly higher proportion of fines, this subsurface runoff was not so noticeable.

Figure 5.1 CEC $_{0\text{-}40mm}$ flowing water was detected at the CECBs/soil interface: Visual evidence at the soil runoff trough interface

To explain the soil decrease infiltration rate it may be assumed that fine particles were translocated vertically from the compost by infiltrating water and washed into the underlying soil blocking pore spaces, thus causing a reduction in hydraulic conductivity. For both CECBs tested, the sealing effect was less evident on the sandy loam treatments due to the inherently greater hydraulic conductivity associated with the sandy loam soil. Further research would be required to validate this assumption.

As stated in the results section, for the 5 years PRSE the CECBs performance for erosion control is comparable to the other treatments, and for the 75 years PRSE the total of TSS loss per plot (g $plot^{-1}$) was greater than all the other treatments. However, some consideration has to be given to the type of sediment generated. With the exception of the CECBs treatments, sediment collected on the filter papers appeared to be predominantly mineral. In contrast, for the CECBs treatments, across all soil types, the material collected was darker and appeared to be comprised of fine organic matter rather than mineral soil. This suggests that the TSS generated from the CECBs was derived from the CECBs and not the underlying soil. This is intuitive, as the CECBs effectively protect the soil surface from raindrop impact, thus preventing the detachment and supply of disaggregated material. As a consequence the total loss of TSS (g) would be overestimated.

The results demonstrate the efficiency of ECBs at preventing soil erosion and regulating runoff. This can be explained by assuming that the runoff from ECBs is not flowing at the ECB/soil interface but rather following preferential pathways through the ECB matrix. With regards to erosion control, the ECBs protect the soil surface, thus preventing detachment sealing formation.

In contrast, the response of the ECB_{straw} to rainfall was less predictable. This could be attributable to the variability in the spatial distribution of straw within the blanket, since after each rainfall event a reorganization of the spatial distribution of straw was observed.

For the 5-year PRSE the hypothesis that CECBs are significantly better than current BMPs in terms of the control of soil storm water runoff from engineered slopes can be accepted.

In contrast, for the 75-year PRSE the hypothesis that CECBs are significantly better than current BMPs in terms of the control of soil storm water runoff from engineered slopes can be rejected.

Water Storage Capacity of CECBs and ECBs was not affected by the soil type, because it is an intrinsic property of the products applied. However due to the dissimilar soil characteristics; principally pore space dimension and hydraulic conductivity, significant differences in runoff and erosion control performance have been detected across the soil types. Thus the hypothesis that the performance of CECBs is consistent across soil types can also be rejected.

Even though it is well known that stepper slopes increase the erosivity of the rain, in our study, the slope gradient did not affected the performance of the treatments. The 5ºslope difference were not sufficient to generate dissimilarity in the results.

The difference observed in relation to the runoff and erosion control performance between the 2 different CECBs may in large part be due to the fact that the $CECB_{0\text{-}40mm}$ contains a significantly higher proportion of > 20 mm compost aggregates as compared with the $CECB_{0\text{-}20mm}$. The > 20 mm compost aggregates were comprised of compost fines and dryer than the main compost and demonstrated a certain degree of hydrophobicity. Further, the greater proportion of > 20 mm compost aggregates allows infiltrating rainfall to pass quickly through larger pores and generate subsurface runoff over the CECB-soil interface. This was particularly evident when the soil hydraulic conductivity (as reduced by the sealing effect of the compost fines blocking pore spaces).
This suggests that the hypothesis that the performance of CECBs is consistent across soil types can be rejected. Further, the results suggest that at least in part, the hypothesis that the PSD of BSI PAS100:2005 compost has a significant effect on the performance of the CECBs can be accepted if the comparative performance of CECBs across soil types is taken into account.

With regards to runoff and leachate ammonium-N concentrations (mg l^{-1}), no differences were found between the treatments. The values were often 2 orders of magnitude lower than the maximum concentration permitted by the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008). This clearly demonstrates that no ammonium-N pollution hazard is expected from the use of CECBs.
The concentration and thus the total loss of orthophosphate-P values were extremely low (between 0.1 and 7 mg l^{-1}) as compared to the UK water quality standard (Table 2.5 and 2.6) in relation to soluble phosphorous (Water Frame Work Directive of the UK Environmental Standard and Condition, 2008). Similar values of orthophosphate-P concentration (1.26 mg l^{-1}) were detected

by Glanville et al., (2004) by analyzing the runoff generated from yard waste CECBs. As demonstrate from the chemical analysis performed in this thesis, even though the Total-P (mg kg^{-1}) content in the compost used was high (3181 mg kg^{-1} for CECB0-40mm and 3145 mg kg^{-1} for CECB0-20mm), the use of CECBs for runoff and erosion control does not present the hazard of orthophosphate-P contamination.

According to the Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government 2008), to consider fresh water unpolluted, the concentration of nitrate has to be less than 50 mg l^{-1}. Both runoff and leachate from CECBs were over 2 times in excess of this limit. This suggested that with regards TON, the hypothesis that CECBs are associated with higher levels of N and P in both runoff and leachate as compared with the current BMPs tested and the untreated controls can be accepted.

The results of the chemical analysis of runoff and leachate suggested that the hypothesis that CECBs are associated with higher levels of N and P in both runoff and leachate as compared to the current BMPs tested and the untreated controls, can be rejected in terms both of orthophosphate-P and ammonium-N.

6 Conclusion

The potential of CECBs as an erosion control technique was relevant only for the 5 years PRSE. Due to the greater WSC of CECBs and high water retention capacity time to runoff initiation was delayed. However, and critically, once the CECBs became saturated, the runoff rate was greater than with all other treatments, including the control. As a consequence the performance of the CECBs in terms of storm water management is highly variable and dependent on the storm duration. Furthermore the performance in runoff and erosion control of the CECBs changed in relation to the soil type used. This could add another source of uncertainty with regards to CECBs application.

Even though CECBs are accepted as Best Management Practices (BMPs) by the United States Environmental Protection Agency (USEPA, 2006a; 2006b) as well as the National Pollutant Discharge Elimination System (NPDES), and are adopted as a BMP by the American Association of State Highway Transportation Officials (AASHTO) and several state-level Departments of Transport, the compost 0-40 grade, compliant with the AASHTO specifications, does not perform any better than the 0-20 mm grade compost.

The concentration of potential contaminants, namely ammonium-N and orthophosphate-P, released via runoff and leachate were comparable to the levels released from the other treatments. Since their concentration (mg l^{-1}) in runoff and leachate was persistently under the maximum level permitted from Nitrate Pollution Prevention Regulation 2008 No. 2349 (UK Government, 2008), in relation to the nitrogen, and Water Frame Work Directive of the UK Environmental Standard and Condition, (Phase-1) (WFD UK TAG, 2008) in relation to the phosphates, no ammonium-N and orthophosphate-P pollution hazard is to be expected by the use of CECBs. Hazardous instead would be the CECBs employment in terms of the total oxided nitrogen (TON). Its concentration in runoff and leachate was constantly over 2 times in excess of the limit.

Due to the small mass of sediment collected (>0.05 g) and potential instrumental errors, the results presented in this thesis with regards to the sediment bound phosphorous cannot be considered as conclusive.

7 Recommendations

The decline in runoff and erosion control performance demonstrated by CECBs under extreme rainfall conditions has significant implications in terms of the reliability of the CECBs for runoff/storm water management and which level of performance should be incorporated within engineering specifications.

In addition, because the runoff and erosion control performance of CECBs critically changes in relation to the diverse soil types, particular attention has to be paid to the design of storm water management systems associated with highway construction projects in relation to the dissimilar substrate.

CECBs 0-40 grade, compliant with the AASHTO specifications demonstrated efficiency in runoff and erosion control, under different USA climatic conditions, as proved by the studies carried out in USA. Instead unsatisfactory performances in runoff and erosion control have been demonstrated by the CECBs 0-40 grade in our work. This suggests that for the climatic condition in the UK a different specification has to be formulated. More effort has to be made to differentiate which CECBs particle size distribution is more suitable for the different soil types.

Further studies are required to fully understand the hydraulic properties of the CECBs, in particular to better quantify the fraction of runoff from CECBs associated with through-flow, surface runoff and/or associated with sub-surface flow at the CECB-soil interface. Furthermore, the relationship between PSD and CECB hydraulic properties needs to be clarified.
The changes in soil characteristic and property variation subsequent to the compost application, which has not been taken into account, must be clarified by supplementary investigations.

Because the demonstrated offsite water contamination risk of total oxided nitrogen (TON) derived from CECBs application, care must be taken when selecting BSI PAS 100:2005 compost for use as CECBs, if nitrate levels in runoff are to remain below the maximum permissible levels. Besides, due to the unsatisfactory results achieved concerning the sediment bound phosphorous, further research would need to be undertaken to evaluate the CECBs' sediment bound phosphorous contamination risk.

From the critical evaluation of the treatment under study in our work, in terms of storm water management the ECB_{coir} treatment was the most predictable across all soil types. ECB_{coir} treatments generated a more reliable and uniform rate of runoff for the duration of the simulated storm events, as compared to all the other treatments.

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